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Integrated Data Collection Analysis Project: Friction Correlation Study

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14. ABSTRACT

The friction sensitivity of new main-charge explosive formulations must be understood while investigating and characterizing a new material and for qualification/ fielding purposes. Sensitivity is measured in comparison to Composition B or a similarly qualified main charge material (such as PETN or RDX). The methods authorized in AOP-7 include Pendulum Friction, Rotary Friction, Sliding Friction (ABL), BAM Friction and Steel/Fiber Shoe Methods. The purpose of this study was to quantify a general correlation between the BAM Friction and ABL Sliding Friction apparatuses across main-charge high explosive materials and formulations, to further the general understanding of friction sensitivity in main charge high explosive ingredients and formulations and to maintain the utility of historical data while transitioning from mortar and pestle to steel pinch point friction sensitivity. This project provides an experimental methodology which results in a statistical correlation between the BAM Friction and ABL Sliding Friction apparatuses. Prediction of ABL values from BAM data is significantly more accurate with 89% accuracy for μ and 83% accuracy for σ using the derived correlation expressions. Prediction of BAM μ is only possible with 57% accuracy and σ with 62% accuracy. The observations in this study are based solely on the sensitivity of the energetics, and do not take into account any of the variation in ability to initiate due to mixture properties, or any interactions between the test apparatus and the energetic material. Any measureable characteristics of the initiation methods of the test apparatus (such as roughness of the interface) have not been explored as factors of the experiment and are classified as one of two levels in a single categorical factor: BAM or ABL friction apparatus. This study serves as a solid starting point for further research efforts in the ability to predict energetic sensitivity amongst disparate testing methods.

15. SUBJECT TERMS
Small- scale safety testing, friction testing, ABL friction, BAM friction, sliding friction, friction correlation, friction sensitivity

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1. OBJECTIVE

The objective of this project is to quantify a general and widely applicable correlation between the βundesanstalt für materialprufung (BAM) Friction and Allegheny Ballistics Laboratory (ABL) Sliding Friction apparatuses across main-charge high explosive materials and formulations, to further the general understanding of friction sensitivity in main charge high explosive ingredients and formulations and to maintain the utility of historical data while transitioning from mortar and pestle (such as the BAM) to steel pinch point (such as the ABL) friction sensitivity measurements.

2. INTRODUCTION/BACKGROUND

The energetic materials in filled end-items, experience a number of environments during their life cycle; from initial formulation and testing through production, item filling, transport and storage. As such, it is crucial that materials be safe to work with, handle and store. Transportation, storage and handling regulations for energetic materials require all new materials be qualified to ensure they have a similar sensitivity to the current inventory of compounds or formulations.[1, 2] This generally begins with small-scale safety testing to understand the sensitivity of a new compound or formulation. Sensitivity testing includes ignition temperature, response when ignited, electrostatic discharge, impact, friction and shock. There are a number of authorized methods to obtain each of these; friction sensitivity can be obtained by Pendulum Friction, Rotary Friction, Sliding Friction (such as the ABL), BAM Friction and Steel/Fiber Shoe Methods.[3, 4] Within each of these accepted methods, there are countless nuances amongst laboratories which make direct comparison between locales extremely challenging. By comparing a new material to high-purity well-understood standard materials, such as PETN, Composition B and/or RDX, laboratories can better account for variability in these types of measurements; however, meaningful correlations are lacking between the various tests.

Recently, there have been a number of efforts and discussions aimed towards standardizing and correlating methods to improve data sharing.[5, 6] This research effort falls within the larger Integrated Data Collection and Analysis (IDCA) program which was funded and initiated by the Department of Homeland Security to facilitate standardization and data sharing between DoD, DOE, other US and international government laboratories and commercial partners. The IDCA group primarily focuses on the study of improvised or homemade explosive materials and has performed a large round robin exchange amongst DoD and DOE laboratories with 16 homemade explosive materials and 3 standard military explosive materials. Efforts such as these have called attention and garnered support for standardization and the need to correlate small-scale safety testing methods .[7]

The Air Force Research Laboratory at Eglin AFB has historically used the BAM friction apparatus for all safety testing and qualification and has a wealth of historical data using this apparatus.[8] This friction sensitivity method mimics the antiquated mortar and pestle environment which is no longer utilized in the formulation and processing of energetic material formulation. Until recently, this was the preferred method of friction testing and continues to be a standard method in Europe.[9] In 2014, the United Nations established the ABL friction apparatus as a recommended method for obtaining friction sensitivity.[10] The ABL apparatus mimics the stainless steel pinch points which are experienced by energetic materials during formulation and processing and is rapidly gaining in popularity, particularly in the U.S.[11]

The literature does not have many examples of attempts to develop correlations between disparate small-scale safety testing methods. Those that have tried, resulted in limited success; some degree of correlation was found for high explosive materials in impact testing and another group was able to develop a translational function linking Rotary and BAM friction.[12-14] The most recent study looked at 19 homemade explosives in an attempt to find a translational function or to develop a general correlation between the ABL and BAM apparatuses. Unfortunately, they were only able to highlight some phenomenological relationships and concluded that the methods are too dissimilar for correlation.[15] This study differs in that it is isolated to high explosives of interest for military applications, it simplifies the complex characteristics of the initiation process for the test methods into two discrete factors and it utilizes statistical analysis to assist in development of the correlation. This study is a first attempt to develop a meaningful and useful correlation between these disparate methods so that the Air Force Research Laboratory Munitions Directorate (AFRL/RWM) can move forward with the ABL friction testing apparatus while maintaining useful historical data and to provide a statistical experimental methodology for further standardization amongst other research and production laboratories.

3. EXPERIMENTAL METHODOLOGY

3.1 Experimental Apparatuses

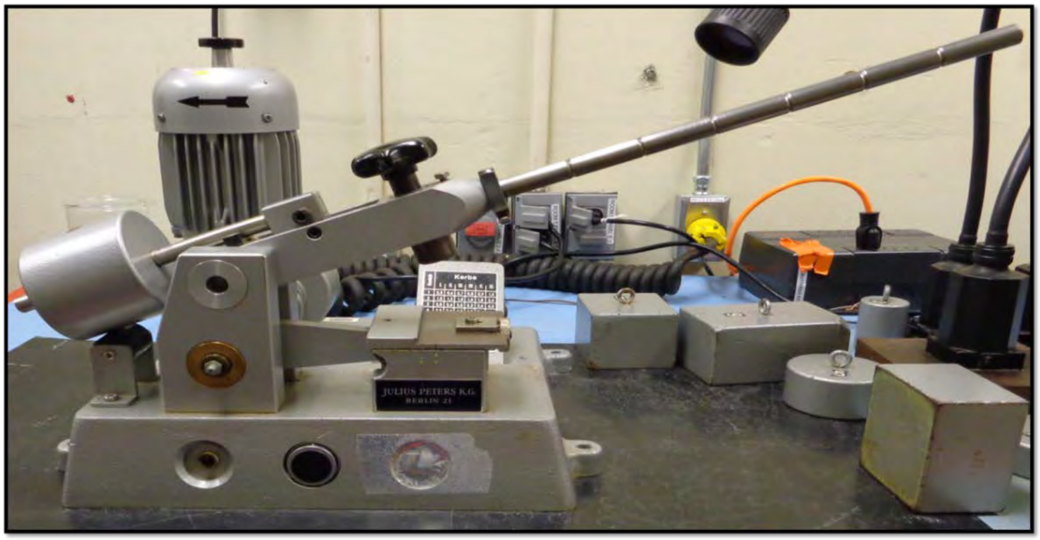

Figure 1. BAM Friction Apparatus

The BAM friction apparatus, Figure 1, is the standard sized friction load table manufactured by Julius Peters Company of Berlin, Germany (no longer in operation).[16] It measures the friction sensitivity response of an energetic material placed between a porcelain plate and pin, Figure 2, with some force being exerted down as a result of a weight, Table 1, placed on the friction arm at discrete notches (corresponding to some load/force N, Table 2). The plate is then moved at a fixed speed (10 mm in 1 sec) with a single unidirectional motion. The two porcelain surfaces are roughened with finish lines normal to the direction of motion. This test apparatus mimics the friction environment of a mortar and pestle which is typically no longer utilized during energetic material formulation and processing, such as high shear mixing.[8]

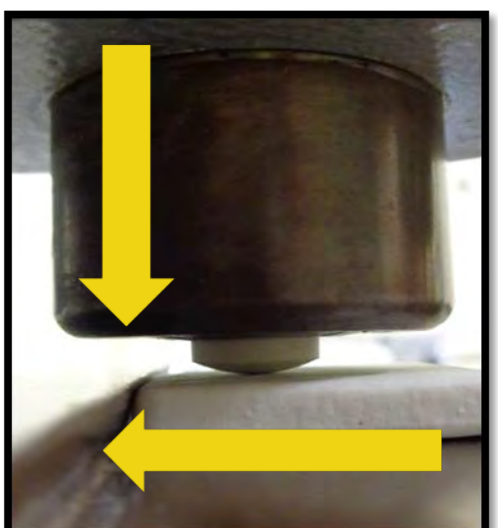

Figure 2. Porcelain pin and plate of BAM Friction Apparatus

Table 1. Mass of Weights No. 1-9[8]

Weight No.	1	2	3	4	5	6	7	8	9
Mass (g)	213	493	1053	1614	2174	3293	4414	6655	10005

Table 2. Loads for Weights No. 1-9 at Positions 1-6[8]

Weight No.	Notch	Load (N)	Weight No.	Notch	Load (N)
1	1	**5**	4	6	**60**
1	2	**6**	5	4	**64**
1	3	**7**	5	5	**72**
1	4	**8**	5	6	**80**
1	5	**9**	6	3	**84**
1	6	**10**	6	4	**96**
2	2	**12**	6	5	**108**
2	3	**14**	7	3	**112**
2	4	**16**	6	6	**120**
2	5	**18**	7	4	**128**
2	6	**20**	7	5	**144**
3	2	**24**	7	6	**160**
3	3	**28**	8	3	**168**
4	1	**30**	9	1	**180**
3	4	**32**	8	4	**192**
3	5	**36**	8	5	**216**
3	6	**40**	8	6	**240**
4	3	**42**	9	3	**252**
4	4	**48**	9	4	**288**
4	5	**54**	9	5	**324**
5	3	**56**	9	6	**360**

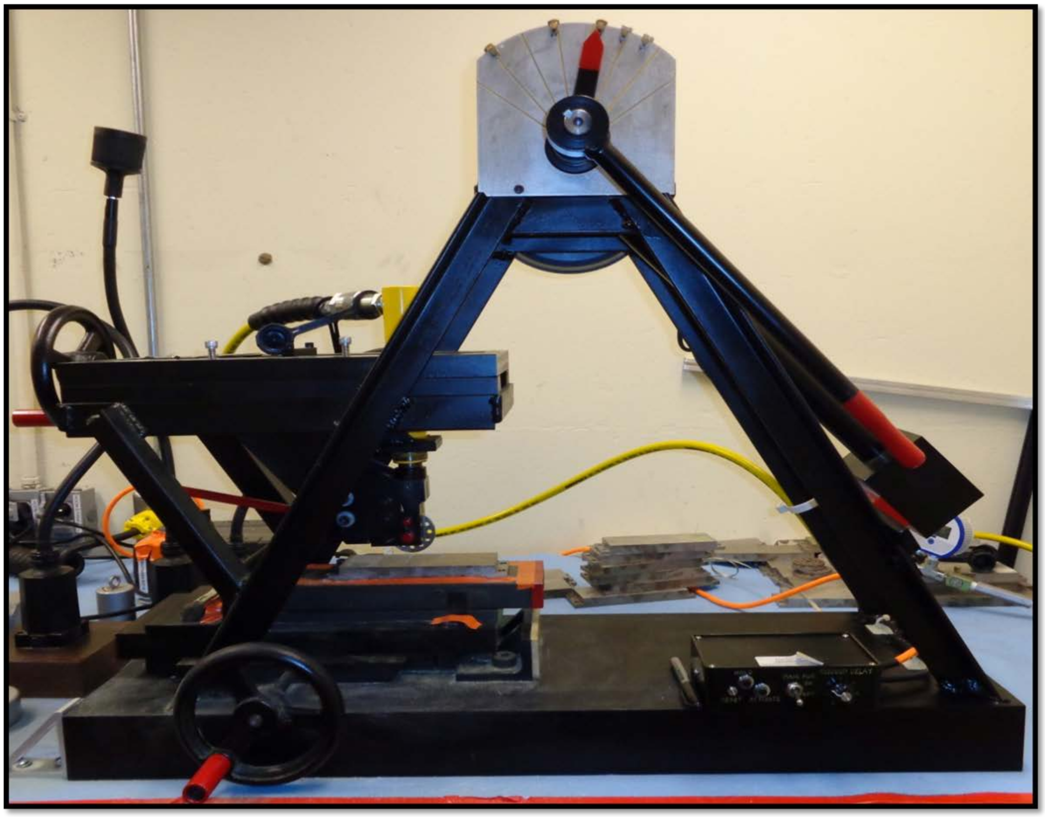

Figure 3. ABL Sliding Friction Apparatus

The ABL sliding friction apparatus, Figure 3, measures the friction sensitivity response of an energetic material placed between a fixed steel wheel and steel anvil with finish lines normal to the direction of motion, Figure 4.[16] A variable compressive force is applied downward through the wheel hydraulically (50-1995 psi). The 5 kg pendulum impacts (8 ft/sec is the standard used herein) onto the edge of the anvil (60 mm by 165 mm steel plate), propelling it forward 25.4 mm at a known velocity perpendicular to the compressive force being applied through the non-rotating wheel. This test apparatus mimics the friction environment of steel pinch points which is seen extensively during the course of energetic material formulation and processing.[11]

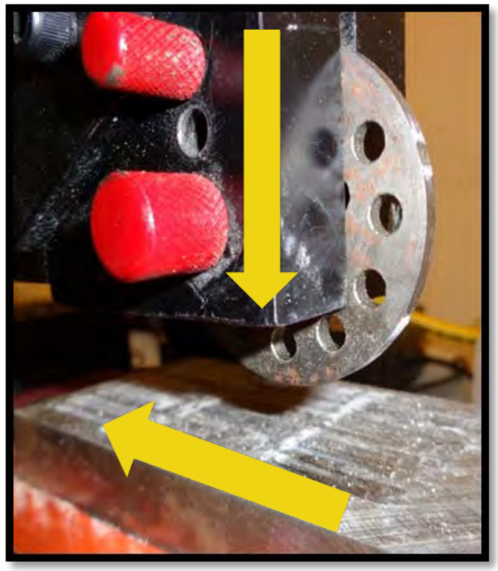

Figure 4. Anvil and non-rotating wheel of ABL Sliding Friction Apparatus

Friction sensitivity for both test apparatuses is the result of the test material either reacting (Go: reaction occurs – initiation in the form of detonation, deflagration, etc.) observed through smoke, fire, a pop or flash of light or not reacting (No-Go: no reaction occurs), reported in a binary manner with 1 representing a Go and 0 a No-Go. Traditionally, the experimentalist will report sensitivity by the Threshold Initiation Level (TIL). Qualification testing begins at a mid-value pressure or mass and works upward until a Go is achieved. Testing will then start moving down in pressure or mass, repeating at a given measurement until either a Go is achieved (followed by further steps down in pressure or mass) or 20 repetition results of No-Go responses.[2-4] The sensitivity threshold is quantified by the estimate of the upper bound at which 20 trials result in No-Go results. This No-Go threshold is then compared to that of a high-purity and well-known standard material (PETN, RDX, Comp B, etc.).[3, 4]

3.2 Test Matrix

For traditional sensitivity testing, 10 Go responses at a particular level and 10 No-Go responses at a lower level establishes the bounds of sensitivity for acceptance or rejection. This method provides information at the tails of reaction distribution, but not necessarily much information about the reaction probability between the two zones. For this study, a new methodology was devised, Figure 5, in order to gain additional responses above and below the traditional threshold response. The test matrix in Figure 5 is designed to more thoroughly probe the zone of mixed results, where a Go or No-Go are equally likely to happen, by beginning testing in a zone where consistent Go responses are expected then moving down to the threshold (consistent No-Go is expected) then back up to where the upper limit of consistent Gos are expected. This matrix is explained thoroughly below and serves to map out the reaction probability distribution function for each material. The appendix contains completed test matrices from testing.

	kg	Down						Up						Summary	
		1	2	3	4	5	6	1	2	3	4	5	6	Go	No-Go
BAM	36.0													0	0
	32.4													0	0
	28.8													0	0
	25.2													0	0
	24.0													0	0
	21.6													0	0
	19.2													0	0
	18.0													0	0
	16.8													0	0
	16.0													0	0
	14.4													0	0
	12.8													0	0
	12.0													0	0
	11.2													0	0
	10.8													0	0
	9.6													0	0
	8.4													0	0
	8.0													0	0
	7.2													0	0
	6.4													0	0
	6.0													0	0
	5.6													0	0
	5.4													0	0
	4.8													0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

	psi	Down						Up						Summary	
		1	2	3	4	5	6	1	2	3	4	5	6	Go	No-Go
ABL	800													0	0
	660													0	0
	560													0	0
	420													0	0
	370													0	0
	320													0	0
	240													0	0
	180													0	0
	130													0	0
	100													0	0
	50													0	0

Sample ______________

Date ______________

Temp ______________

RH ______________

Overview		
Down	1	No-fire search
	2	No-fire location
	3	No-fire confirmation
Up	4	All-fire search
	5	All-fire location
	6	All-fire confirmation
	7	Mixed-results check

Figure 5. Testing Matrix for BAM (left) and ABL (right) friction apparatuses

3.3 Test Matrix Procedures

1. Start testing using a stress (mass - kg or pressure - psi) that the experimentalist expects would induce 10 initiations out of 10 runs, recording data in the 'down' columns (1 for a Go, 0 for a No-Go).
2. Test a single sample, if an initiation is generated, continue to step down in single increments until a non-initiation is generated.
3. Continue testing at the non-initiation level until either 5 consecutive non-initiations are achieved; or a single initiation is generated.
4a. If a single initiation is generated, repeat step 2 and proceed.
4b. If 5 consecutive non-initiations are achieved, drop down one more step, and repeat 5 non-initiations.*

5. If 5 non-initiations are successfully achieved at this level, starting at two levels up (lowest level above 5 consecutive non-initiations), step back up in smallest increments possible (testing a single sample at each stress level) until an initiation is generated. Record data in the 'up' columns (1 for a Go, 0 for a No-Go).
6. Continue testing at that level until either 5 consecutive initiations are achieved; or a single non-initiation is generated.
7. If a single non-initiation is generated, continue to step up incrementally, testing a single sample at each stress level, until an initiation is generated.
8a. If an initiation is generated, repeat step 6 and proceed.
8b. If 5 consecutive initiations are generated, step one more level up, and repeat the 5 consecutive initiations.**
9. Mixed Results: If the highest stress value which achieved a non-initiation is lower than the lowest stress value which achieved an initiation (no 'overlap' region), run additional tests at or between these stresses until an overlap region is achieved. This data can be recorded in either column.
* If a single initiation occurs during testing the 5 confirmatory non-initiations, step down one more level and repeat from step 3.
** If a single non-initiation occurs during testing the 5 confirmatory initiations, step up one more level and repeat from step 7.

3.4 Material Selection

Polyurethane based-binder systems, melt-castable explosive formulations and raw explosive ingredients were utilized in this study in order to develop a correlation which would be applicable to a wide range of materials (raw and formulations) to include experimental or developmental materials. AFX-196, AFX-256, MNX-808, PBXN-109, PBXN-110, RDX (Class V, Type II), HMX (Class V, Type II) and FOX-7 were chosen to represent the broad range of materials for this study.

3.5 Statistical Analysis

A generalized linear model, was utilized for the statistical analysis of the binary response Go and No-Go friction sensitivity results (1 input for Go, 0 input for No-Go). This model assumes a cumulative normal distribution for the probability of an event occurring given a certain stress level (weight on the BAM or pressure on the ABL) defined by the parameters μ (mean) and σ (standard deviation), accounting for left- and right-censoring of the data, Figure 6. Empirical models were developed to relate the parameters, μ and σ, expected on the BAM from the ABL data and vice versa.[17-19]

The data was analyzed as the test results were performed to ensure that the regression curve had informative confidence bounds. In the event that the confidence bounds were uninformative (i.e. they diverged to 1 and 0, indicating that the probability of occurrence is somewhere between “never occurring” and “always occurring”) additional test points were proposed to improve the regression equation.

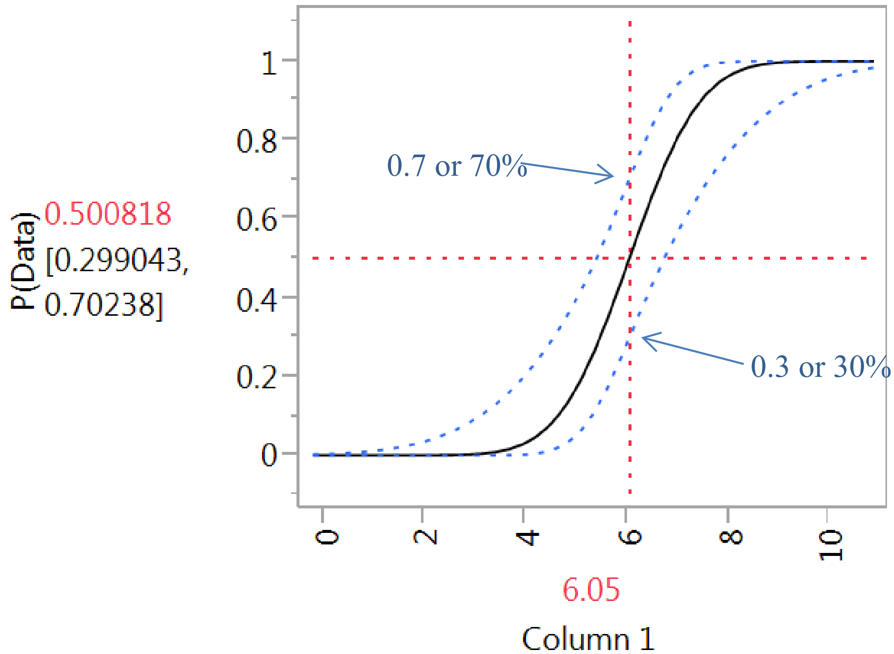

Figure 6. Example of the generalized linear model – Probit (Probability Unit) regression analysis with confidence bounds on the probability curve

From each set of Go/ No-Go data generated for a particular explosive, a logistic regression curve was generated (individual regression curves provided in the appendix). An example of the regression curve for HMX tested using the BAM friction apparatus is shown in Figure 7. The data points represent the response of the explosive given a certain stimulus (weight and position on the BAM friction apparatus). The curve is a maximum likelihood estimate of a fit line through the probability ratios.

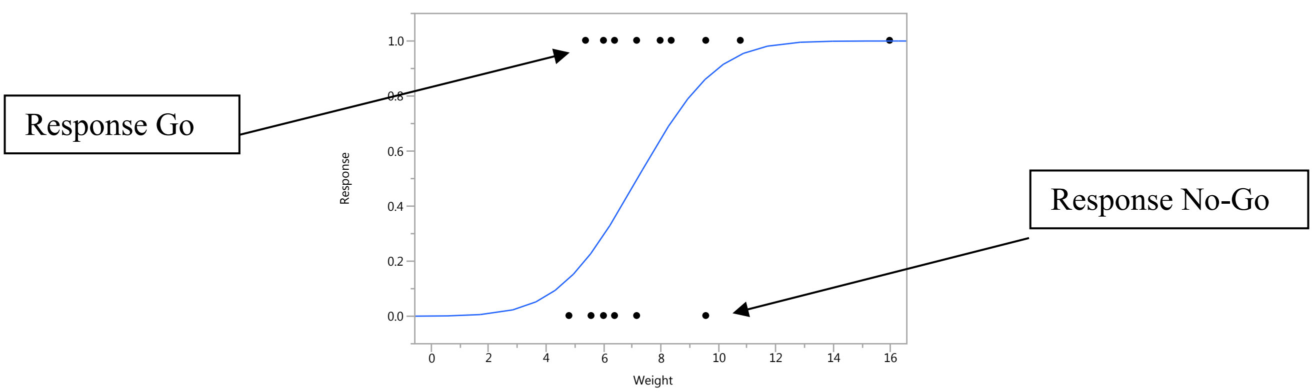

Figure 7. This graph highlights the lack of information in the zone of mixed results where the analysis is less meaningful due to low confidence between a Go and No-Go response

The curve shown in Figure 8 displays the same data, but this time with the confidence bounds of the curve fit included. This curve incorporates information from the zone of mixed results and provides information along the entire curve.

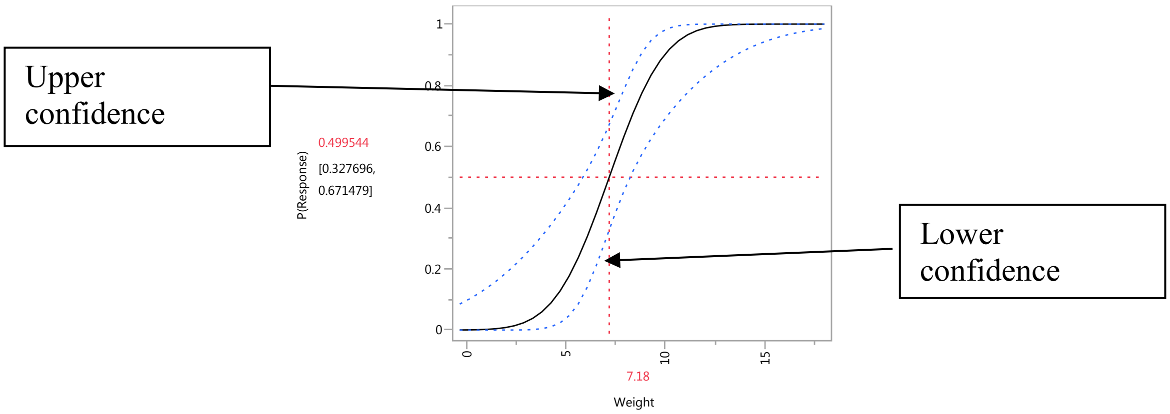

Figure 8. This graph highlights the more useful information provided through utilization of the new test matrix and use of the Probit regression model

In order to generate an estimate of probability, a link function must be used that follows the laws of probability; specifically that the probability can never be less than zero or greater than one. In this case, a Probit link function was used. The Probit regression analysis is based on the cumulative normal distribution with the parameters μ and σ.[19]

4. RESULTS AND ANALYSIS

4.1 Data Analysis

The data for each series was fit to the cumulative normal distribution function written in linear form with parameters β_0 and β_1:

$$P(x) = \frac{1}{2}\left[1 + \text{erf}\ (\beta_1\, x + \beta_0)\right] \tag{1}$$

Where *erf* is the error function and *x* is the mass or the pressure independent variable of the BAM or ABL test, respectively. The parameters μ and σ were then calculated from the maximum likelihood fit parameters. The relationships between the linear fit parameters (β_0 and β_1) and the parameters of a normal distribution (μ and σ) are shown below in Equations 2 and 3.

$$\sigma = \frac{1}{\beta_1} \tag{2}$$

$$\mu = -\sigma\, \beta_0 \tag{3}$$

The parameters μ and σ are sufficient to describe a cumulative normal distribution, the results of which are shown in Table 3 for the materials tested. The parameters μ and σ are the factors which this study is attempting to predict. The objective is the prediction of the response parameters of one apparatus based upon the experimentally derived parameters of the other across the range of materials. After the parameters of each test were obtained experimentally, Table 3, the relationship between the BAM and the ABL test apparatuses was explored mathematically.

4.2 Selection of Parameters

It is noteworthy to point out that the modeled parameters were not either β_0 and β_1 or μ and σ but a combination of β_1 and μ. It was not possible to construct a mathematical model of β_0 for the ABL apparatus using the β_0 and β_1 values from the BAM apparatus or conversely for the β_0 for the BAM apparatus using the β_0 and β_1 values from the ABL apparatus. The experimentally collected data values were of a similar order of magnitude but varied too significantly amongst individual data pairs, shown in Figure 9. Discarding data pairs which differed too greatly in magnitude would have resulted in significant shrinkage of the data set due to the large relative differences between the majorities of the data pairs. The differences found in β_0 values when performing a matched pair's analysis were not statistically different in enough of the pairs to make an informative regression. The location parameter, β_0, did not vary as expected (uniformly) to model without the effect of the scale parameter.

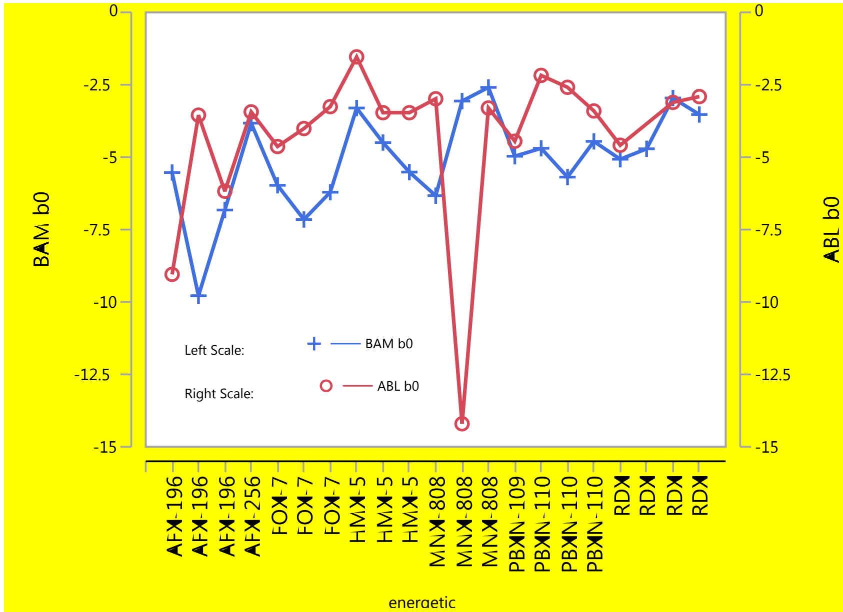

Figure 9. Comparison of experimentally derived values for β_0 on BAM (left) and ABL (right) for each sample tested

The β_0 term varied between the BAM and ABL apparatuses almost randomly and to such an extent that in order to construct a model that represented μ, a direct estimate of μ was necessary. Through modeling µ directly, the effect of the β_0 term was reduced. Otherwise, estimates of μ would have been based entirely on σ (or its negative inverse, β_1) which would be meaningless because the estimates of μ are orders of magnitude different. The downside to this type of approach is that the location effect (mean) is confounded with the scale effect. This effectively makes the assumption that it is a property of the individual apparatus and how each material interacts with a particular apparatus, which may not be an erroneous assumption.

4.3 Preliminary Correlation

A preliminary examination of how closely the experimentally derived signals for each material track to one another allows for a cursory look at the correlation and consistency in testing. The magnitude and direction of the differences in the experimentally obtained parameters for the BAM and ABL apparatuses are shown in Figure 10. The two lines in each graph are to different scales so direct comparison is not possible.

The overlay plots show divergence for some of the heterogeneous materials (especially apparent in the melt-castable materials) and more consistency in variation of direction and magnitude in the single component powder materials (RDX and HMX). When replicate samples are averaged, consistency in magnitude and direction is observed between the BAM and ABL apparatuses, Figure 11. Data for AFX-256 and PBXN-109 are excluded as they are derived from a single sample. This might indicate that variation is due to the heterogeneous nature of the melt-castable and polyurethane based formulations (natural variation of material) or an interaction between the fundamental function of the apparatus and the mixture properties of the materials.

In the case of melt-castable samples (AFX-196 and AFX-256), there was increased sample variability likely due to sample preparation procedures in which the samples are ground and sieved prior to testing. Polyurethane based formulations were cast into strips for friction testing and as a result samples were very uniform although in both cases the materials are heterogeneous mixtures. The data from these samples are included in the development of the correlation but should be explored further to identify sources of variability and to further strengthen the correlation.

Surprisingly, it appears that instrument variability is not as large as previously believed. Results from both instruments are reproducible from run to run in the short term (not necessarily on the time-scale to observe long term drift). It would be worthwhile to study this further to more accurately quantify instrument variability for the sensitivity testing community.

Table 3. Estimated maximum likelihood parameters for materials tested

Material	BAM β_0	BAM β_1	BAM μ	BAM σ	ABL β_0	ABL β_1	ABL μ	ABL σ
AFX 196	-6.83	0.629	10.85	1.59	-6.174	0.0045	1365.68	221.19
AFX-196*	-9.78	0.752	13.01	1.33	-3.549	0.0034	1029.46	290.05
AFX-196*	-5.53	0.343	16.15	2.92	-9.046	0.0087	1042.48	115.24
AFX-256	-3.83	0.196	19.55	5.11	-3.436	0.0092	375.22	109.21
FOX 7	-6.21	0.435	14.27	2.30	-3.255	0.0026	1259.34	386.85
FOX 7	-7.15	0.454	15.76	2.20	-4.011	0.0031	1277.11	318.4
FOX 7	-5.97	0.263	22.74	3.81	-4.632	0.0023	2011.33	434.2
HMX	-5.52	0.912	6.050	1.10	-3.464	0.019	178.21	51.45
HMX	-4.50	0.859	5.24	1.17	-3.464	0.019	178.21	51.45
HMX	-3.30	0.46	7.180	2.17	-1.537	0.012	125.45	81.61
MNX-808	-2.59	0.112	23.07	8.90	-3.302	0.0054	611.03	185.07
MNX-808**	-3.06	0.127	24.20	7.90	-14.20	0.014	1001.95	70.54
MNX-808	-6.33	0.267	23.69	3.74	-2.984	0.0025	1171.29	392.57
PBXN-109	-4.97	0.258	19.28	3.88	-4.449	0.0052	849.47	190.93
PBXN-110	-4.45	0.152	29.27	6.57	-3.404	0.0042	808.99	237.66
PBXN-110	-5.69	0.203	27.98	4.92	-2.588	0.0027	944.5	365
PBXN-110	-4.69	0.197	23.77	5.06	-2.177	0.0025	862.38	396.21
RDX	-3.53	0.369	9.560	2.71	-2.908	0.013	223.91	76.99
RDX	-2.96	0.331	8.931	3.02	-3.109	0.011	271.89	87.45
RDX**	-4.71	0.516	9.130	1.94	--	--	--	--
RDX	-5.07	0.626	8.110	1.60	-4.588	0.015	306.47	66.8

In some cases, data was found to have confidence bounds that failed to converge. In these cases, data was discarded or combined in order to eliminate excess variation in the statistical models. * Indicates that data was combined and ** indicates that data was discarded.

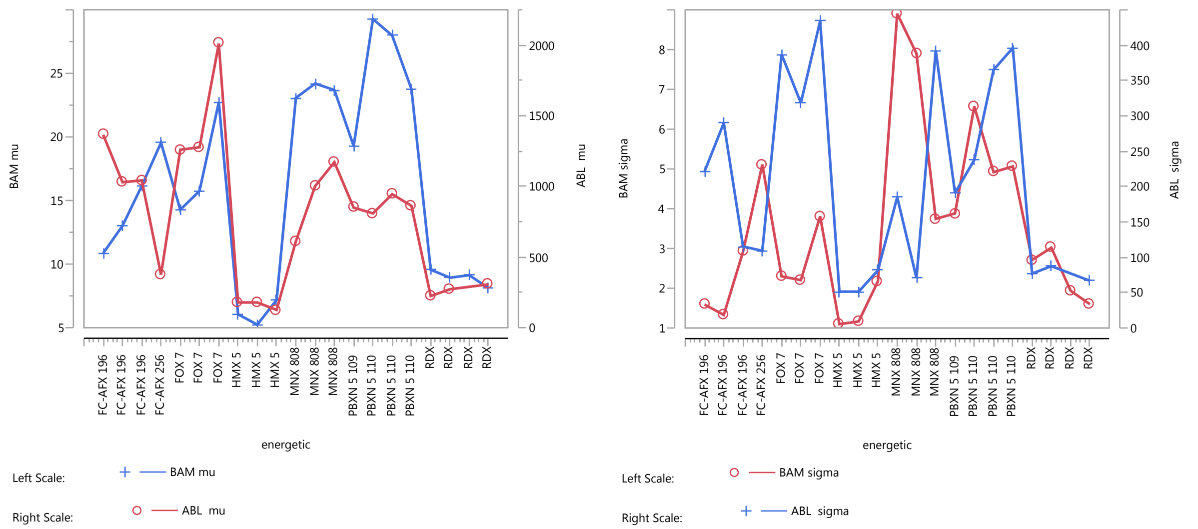

Figure 10. (Left) Overlay plots with the mu signal variation between ABL (red) and BAM (blue) friction apparatuses. (Right) Overlay plots with the sigma signal variation between ABL (blue) and BAM (red) friction apparatuses

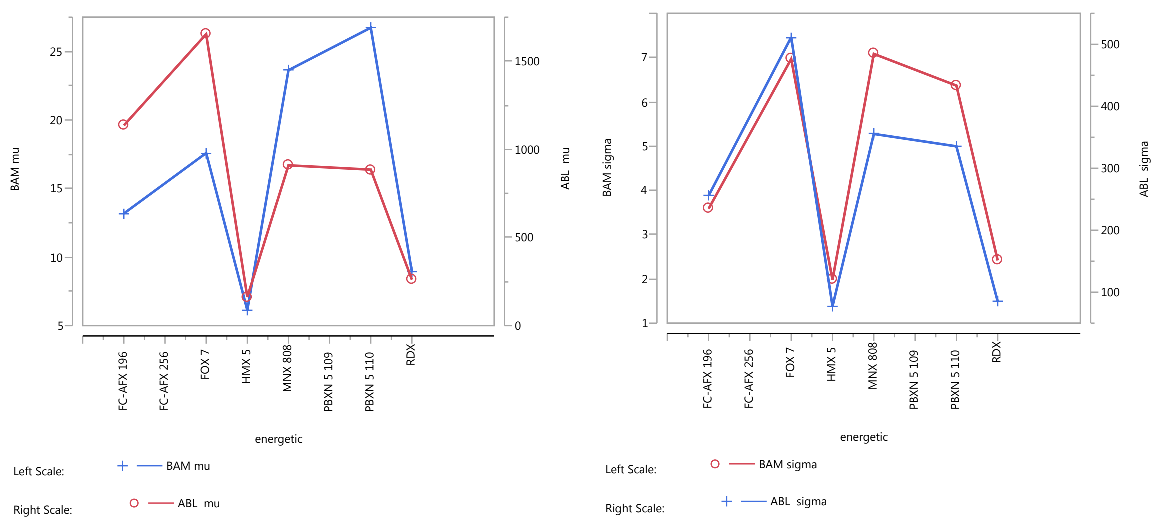

Figure 11. (Left) Overlay plots with the average mu signal responses between ABL (red) and BAM (blue) friction apparatuses. (Right) Overlay plots with the average sigma signal responses between ABL (blue) and BAM (red) friction apparatuses

While the goal of this effort was to provide a single broad and general correlation between the BAM and ABL friction apparatuses it is possible that different classes of materials correlate differently between the two methods. Further, it is worth emphasizing that the powdered energetic materials were sampled from strictly controlled, single-lot, well-characterized standard materials. In contrast, the polymer-based and melt-castable materials were sampled from single lot materials and are heterogeneous in nature. A cursory look at the mean and standard deviation responses of these three classes of materials is given in Figure 12. The groupings suggest that there may be a relationship between the mean response of powders, PBX formulations and wax formulations. A relationship is not readily apparent in the BAM and ABL standard deviation responses for the three types of materials studied. These relationships may be of interest in future investigations.

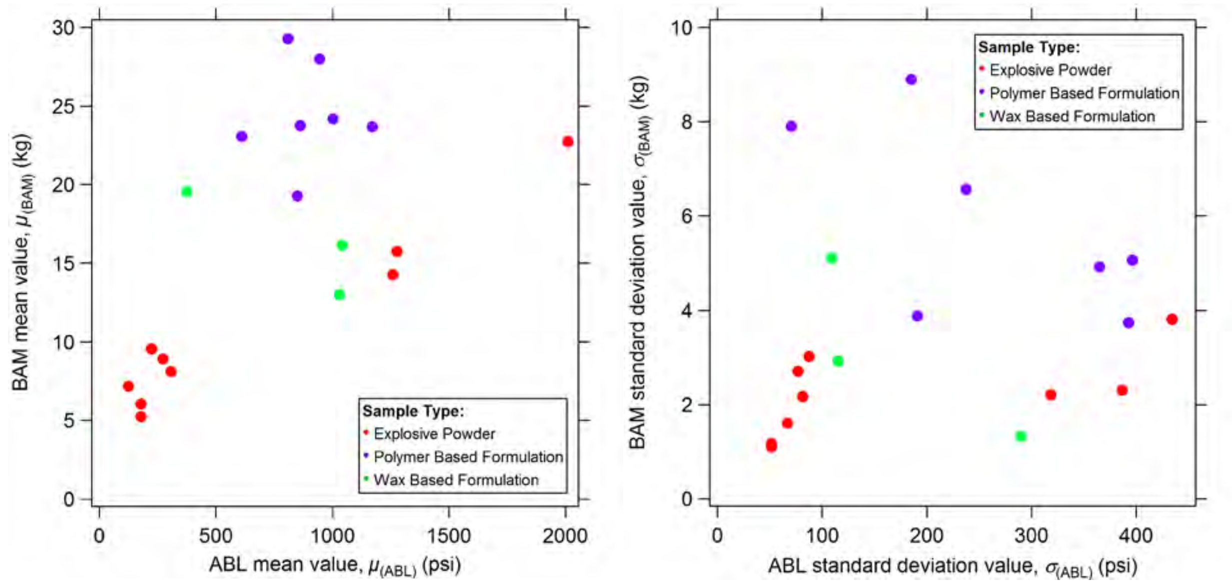

Figure 12. Graphical comparison of mean (left) and standard deviation (right) values for BAM (*x*-axis) and ABL (*y*-axis) measurements of explosive powders (red), polymer-based formulations (blue) and wax-based formulations (green)

4.4 Prediction of ABL Parameters from BAM Results

Prediction expressions were derived for the ABL apparatus from parameters of the BAM apparatus experiments using a combination of the parameters β_0, β_1, μ and σ. The β_0 and β_1 values from the experimental results for the BAM apparatus were used in the prediction expression, shown in Equation 4, to predict the β_1 value for the ABL apparatus. Figure 13 shows a graph of the predicted ABL β_1 values (x axis) plotted against the experimentally derived (actual) ABL β_1 values (y axis) as determined experimentally. All of the materials are within the confidence bounds with the polyurethane-based formulation, MNX-808, having the largest variability between replicate runs and being the furthest from the derived value line.

$$\begin{aligned}\beta_{1\,(ABL)} = {} & 0.013853943839 51 + 0.00296270321481\,\beta_{0\,(BAM)} \\ & +0.02004729198554\,\beta_{1\,(BAM)} \\ & +\{\beta_{0(BAM)} - (-5.1019597)\} \times \{[\beta_{0(BAM)} - (-5.019597)] \times 0.00037714265794\} \\ & +\{\beta_{0(BAM)} - (-5.1019597)\} \times \{[\beta_{1(BAM)} - 0.39684075555556] \times 0.00762552928509\} \\ & + \{(\beta_{1(BAM)} - 0.39684075555556) \\ & \times [(\beta_{1(BAM)} - 0.39684075555556) \times 0.01380030525933]\}\end{aligned} \tag{4}$$

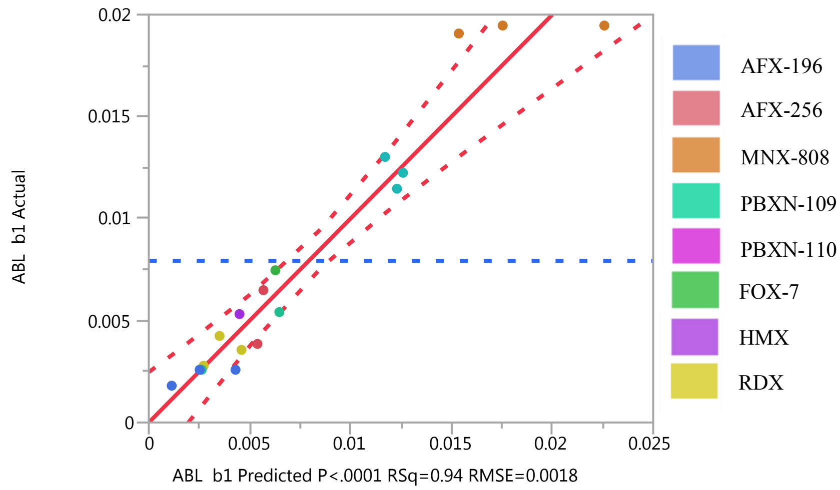

Figure 13. Predicted β_1 values (*x* axis) plotted versus actual β_1 values (*y* axis) for the ABL apparatus for all materials studied

The μ and σ values estimated from the actual ABL experiments were then used to calculate the ABL μ values using Equation 1, above, and the derived expression shown in Equation 5. Figure 14 shows a graph of the predicted ABL μ values (*x* axis) plotted against the actual ABL μ values (*y* axis) as determined experimentally. There is greater deviation in the μ values than seen in the derived β_1 values, with the melt-castable formulations having greatest variability and being furthest from the experimentally derived values.

$$\begin{aligned}\mu_{(ABL)} = {} & 404.636354868987 + 94.1860144503784\,\mu_{(BAM)} \\ & + (-321.54126535698)\,\sigma_{(BAM)} \\ & + \{(\mu_{(BAM)} - 16.2242653429444) \\ & \times [(\sigma_{(BAM)} - 3.54447654427778) \times (-27.350192500987)]\} \\ & + \{(\sigma_{(BAM)} - 3.54447654427778) \\ & \times [(\sigma_{(BAM)} - 3.54447654427778) \times 67.7607275547574]\}\end{aligned} \tag{5}$$

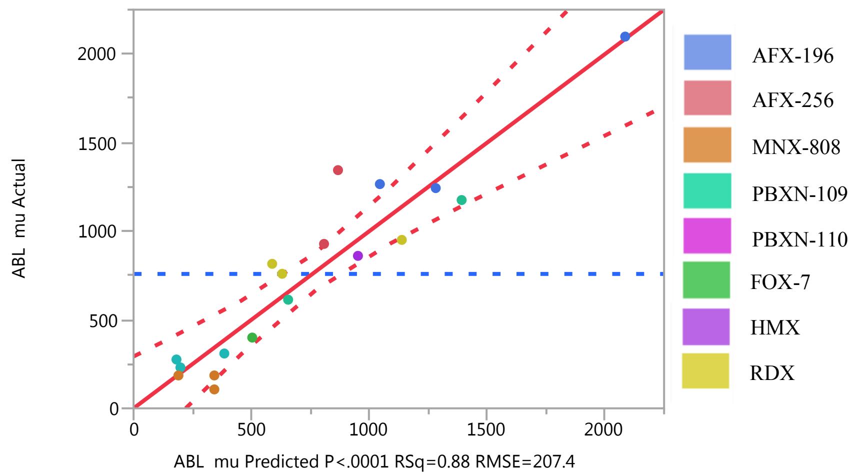

Figure 14. Predicted mu values (*x* axis) plotted versus actual mu values (*y* axis) for the ABL apparatus for all materials studied

4.5 Prediction of BAM Parameters from ABL Results

Prediction expressions were also derived for the BAM apparatus from parameters of the ABL apparatus using a combination of the parameters β_0, β_1, μ and σ. The β_0 and β_1 values from the experimental test results for the ABL apparatus were used in the prediction expression, shown in Equation 6, to predict the β_1 value for the BAM apparatus. Figure 15 shows a graph of the predicted BAM β_1 values (x axis) plotted against the actual BAM β_1 values (y axis) as determined experimentally. Again, the melt-castable formulations and MNX-808 show large variations between runs. The melt-castable samples also fall outside of the confidence bounds more frequently that the other materials.

$$\begin{aligned}\beta_{1(BAM)} = {} & (-0.1062755137965) + \left(-0.0862241340497\,\beta_{0\,(ABL)}\right) \\ & + 3.8754944002461\,\beta_{1\,(ABL)} \\ & + \left\{\left(\beta_{1(ABL)} - 0.00792548688889\right) \right. \\ & \left. \times \left[\left(\beta_{1(ABL)} - 0.00792548688889\right) \times 4769.3489266296\right]\right\}\end{aligned} \tag{6}$$

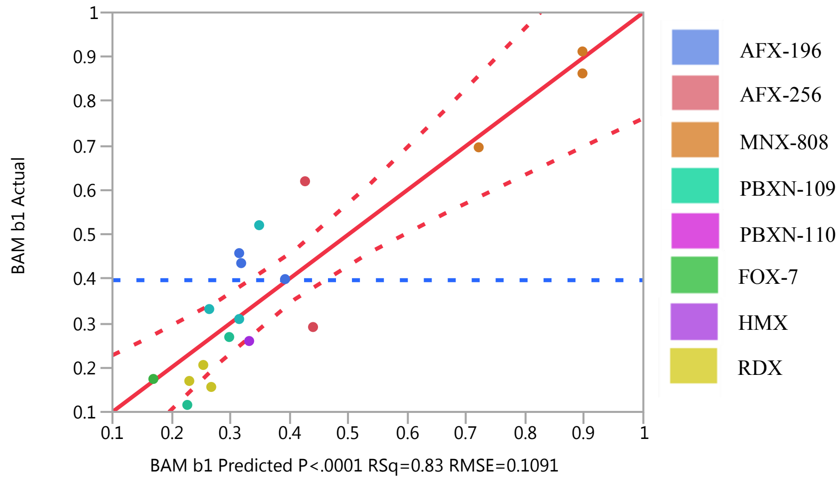

Figure 15. Predicted β_1 values (*x* axis) plotted versus actual β_1 values (*y* axis) for the BAM apparatus for all materials studied

The μ and σ values estimated from the actual BAM experiments were then used to calculate the BAM μ values using Equation 2, above, and the derived expression shown in Equation 7 (where β values refer to ABL β parameters). Figure 16 shows a graph of the predicted BAM μ values (*x* axis) plotted against the actual BAM μ values (*y* axis) as determined experimentally. The melt-castable formulations continue to show variability between runs. Further exploration of sample variability and additional runs of all materials would be very helpful in decreasing variability and improving derived expressions for both apparatuses.

$$\begin{aligned}\mu_{(BAM)} = {} & 8.77389626325093 + 0.04623799900042\,\sigma_{(ABL)} \\ & + \{(\sigma_{(ABL)} - 220.139702508333) \\ & \times [(\sigma_{(ABL)} - 220.139702508333) \times (-0.0001236098308)]\}\end{aligned} \tag{7}$$

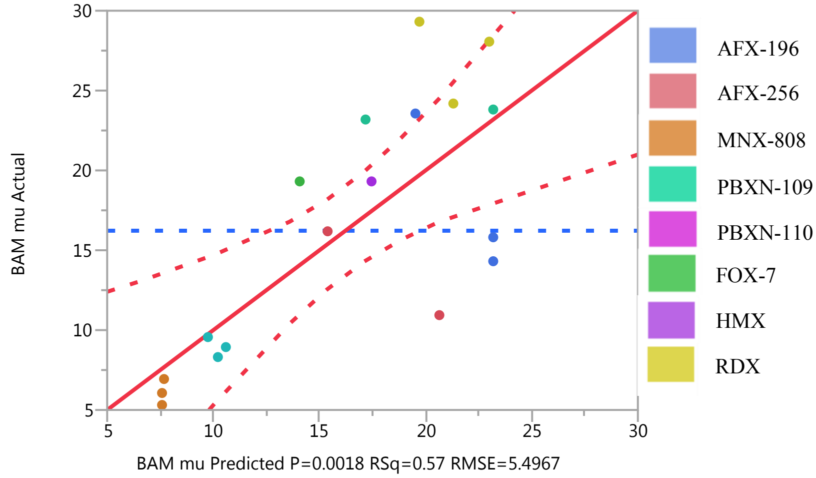

Figure 16. Predicted mu values (x axis) plotted versus actual mu values (y axis) for the BAM apparatus for all materials studied

4.6 Parameter Prediction Fitting

A comparison of how well the predicted (pred) parameter values compare to the parameter values estimated from the test data are shown in Figure 17 for the ABL apparatus and Figure 18 for the BAM apparatus. The sigma values were calculated using Equation 2, above. The 95% confidence interval is displayed in the dark blue shaded regions in the figures. This region represents a probability space associated with a non-random, unknown parameter and is computed as a probability from the data. The 95% prediction interval is displayed as the light blue regions in the graphs. It is associated with a random variable that has not yet been observed within the confines of these experiments, has a specified random probability associated with it at some point within the interval and provides the probability interval for future observations.

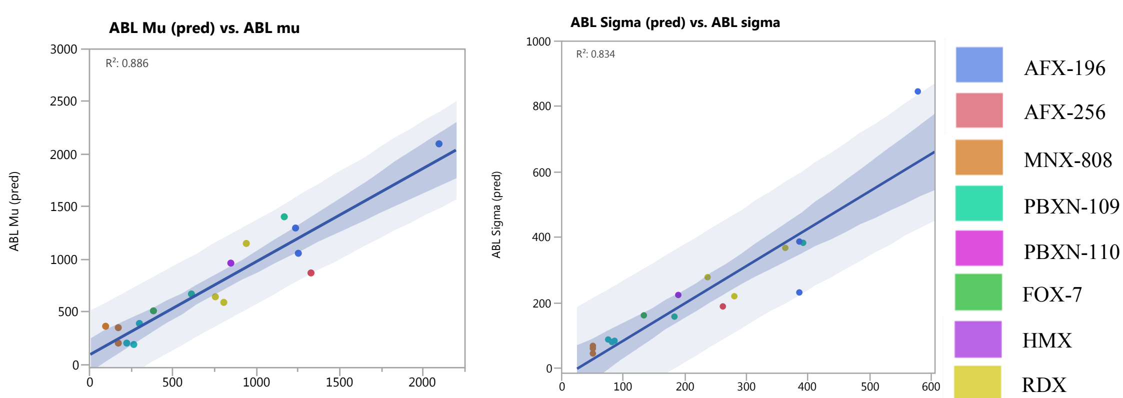

Figure 17. Predicted (pred) mu values (x axis) plotted versus actual mu values (y axis), left, and predicted (pred) sigma values (x axis) plotted versus actual sigma values (y axis), right, for the ABL apparatus for all materials studied. Dark blue region is the 95% confidence interval. Light blue region is the 95% prediction interval.

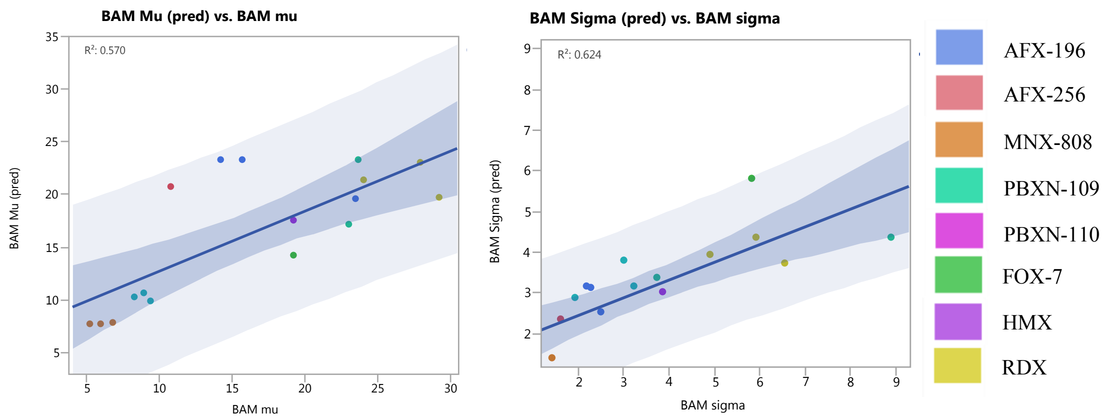

Figure 18. Predicted (pred) mu values (*x* axis) plotted versus actual mu values (*y* axis), left, and predicted (pred) sigma values (*x* axis) plotted versus actual sigma values (*y* axis), right, for the BAM apparatus for all materials studied. Dark blue region is the 95% confidence interval. Light blue region is the 95% prediction interval.

The prediction of ABL values from the BAM data is significantly more accurate than the prediction of BAM values from the ABL data. Using Equations 2, 3, 6 and 7 along with experimental data from the ABL apparatus, BAM μ is predicted with 57% accuracy and σ with 62% accuracy. Using Equations 2, 3, 4 and 5 along with experimental data from the ABL apparatus, BAM values are predicted with 89% accuracy for μ and 83% accuracy for σ. These derived expressions allow for a basic understanding of where to expect historical BAM values to now fall on the ABL apparatus but does not allow accurate prediction of BAM values while transitioning to the ABL apparatus. There remains significant work to be done to obtain a more accurate and generally applicable correlation.

5. CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

Herein is described an experimental methodology which results in a statistical correlation between the BAM Friction and ABL Sliding Friction apparatuses. The correlation has been demonstrated across a variety of materials, including single component explosive powders, and polymer or wax composite explosive formulations. The correlation was found to be significantly stronger in the prediction of BAM values from ABL data than the converse. The observations in this study are based solely on the sensitivity of the energetic materials, and do not take into account any of the variation in ability to initiate due to mixture properties, or any interactions between the test apparatus and the energetic material. Additionally, the study focused on secondary explosive materials and does not extend to propellants, pyrotechnics, primary explosives, etc. Any measureable characteristics of the initiation methods of the test apparatus (such as roughness of the interface) have not been explored as factors of the experiment and are classified as one of two levels in a single variable (categorical factor): BAM or ABL friction apparatus. It is likely that additional data will improve parameter estimates and the ability to predict energetic sensitivity from one friction apparatus to another.

5.2 Future Work

The research presented herein represents an initial study into the development of a correlation between the BAM and ABL friction apparatuses across a broad range of materials. There is a significant amount of work remaining to obtain a solid correlation that works both ways (converting ABL into BAM data and vice versa). To further improve the correlation and ensure its generality, future studies should consider increasing the number of replicate runs for each sample, introducing lot-to-lot variation and including additional materials of interest (raw ingredients, melt-castable, polyurethane based and experimental formulations). The sample preparation for the melt-castable explosives, including grinding method and particle size effects, should be explored. Finally, other variables should be explored (including temperature, humidity, initiation effects, mixture properties and instrument specific variables) to further strengthen the correlation.

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APPENDIX

Individual Probit Regression Curves – Actual vs. Predicted

LIST OF FIGURES

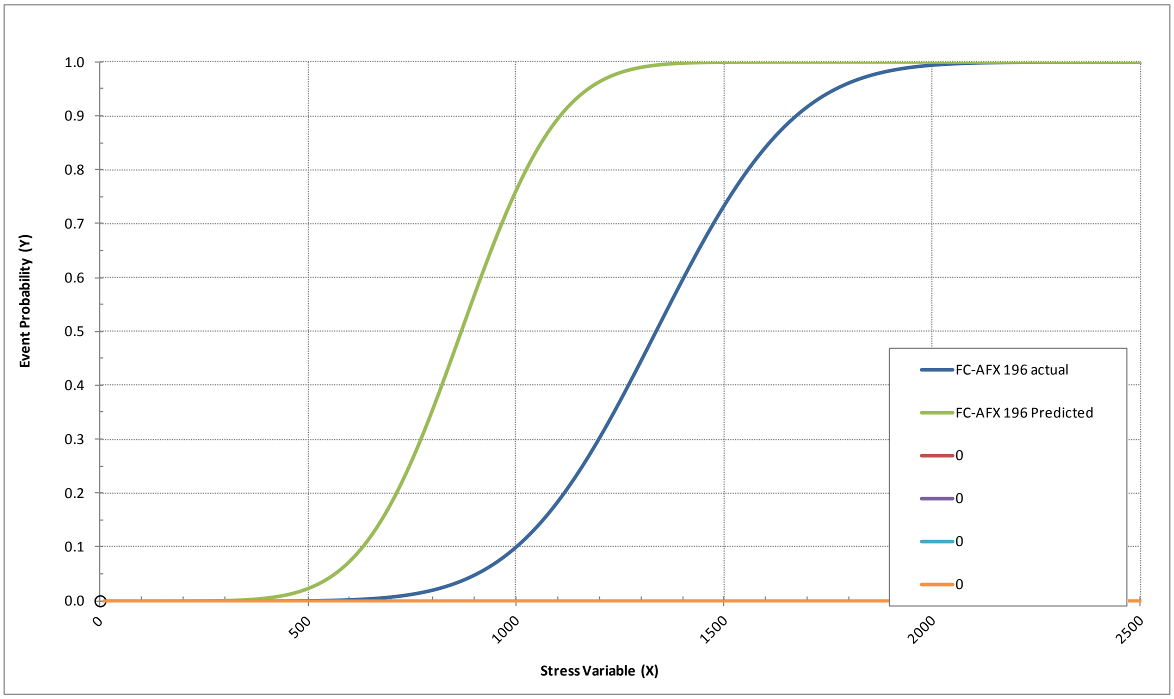


Figure A-1. Probit Regression Curve for AFX-196 sample. Actual experimental data in blue and prediction in green.

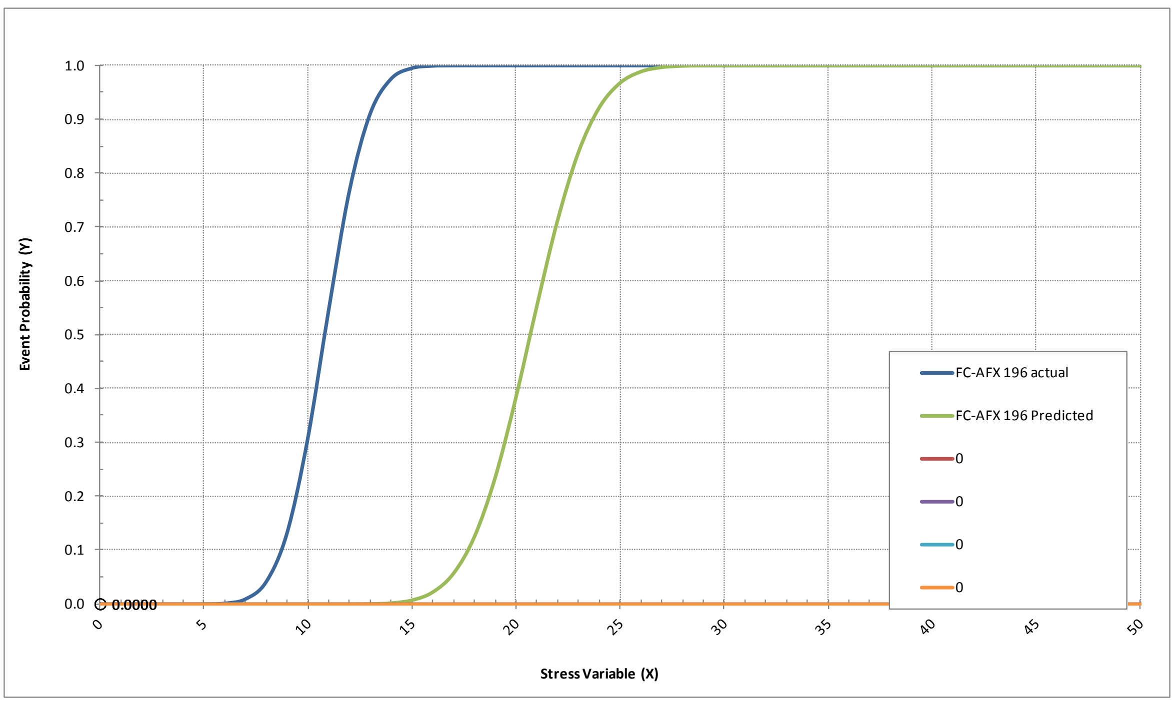


Figure A-2. Probit Regression Curve for AFX-196 sample. Actual experimental data in blue and prediction in green.

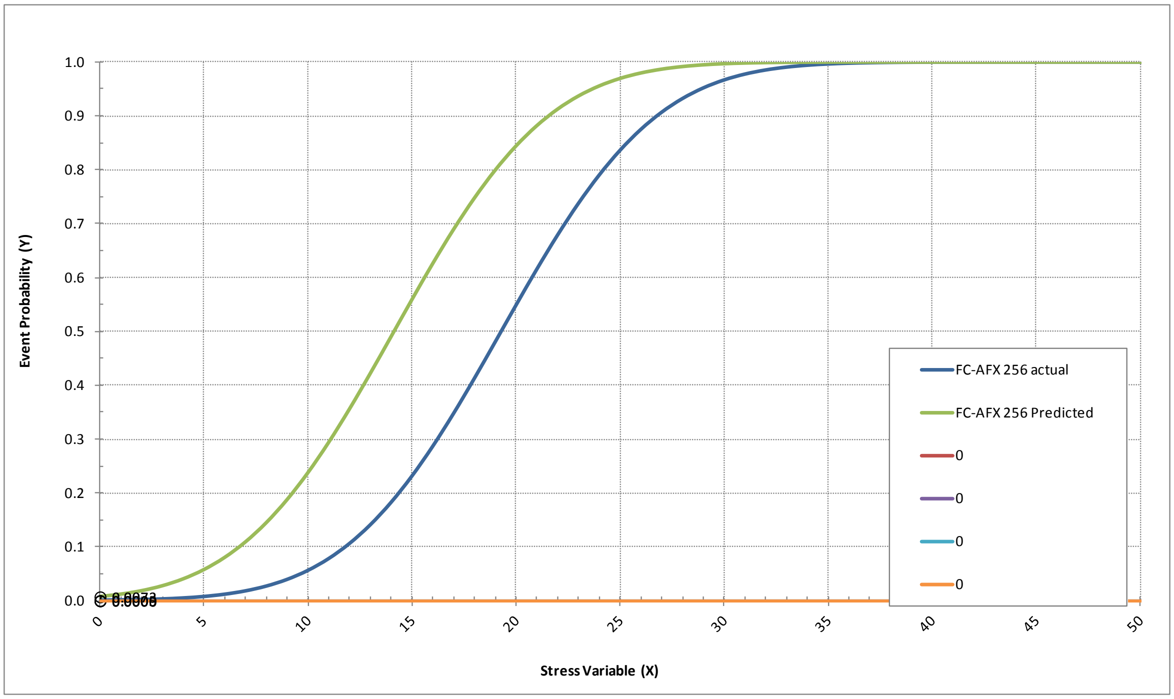


Figure A-3. Probit Regression Curve for AFX-256 sample. Actual experimental data in blue and prediction in green.

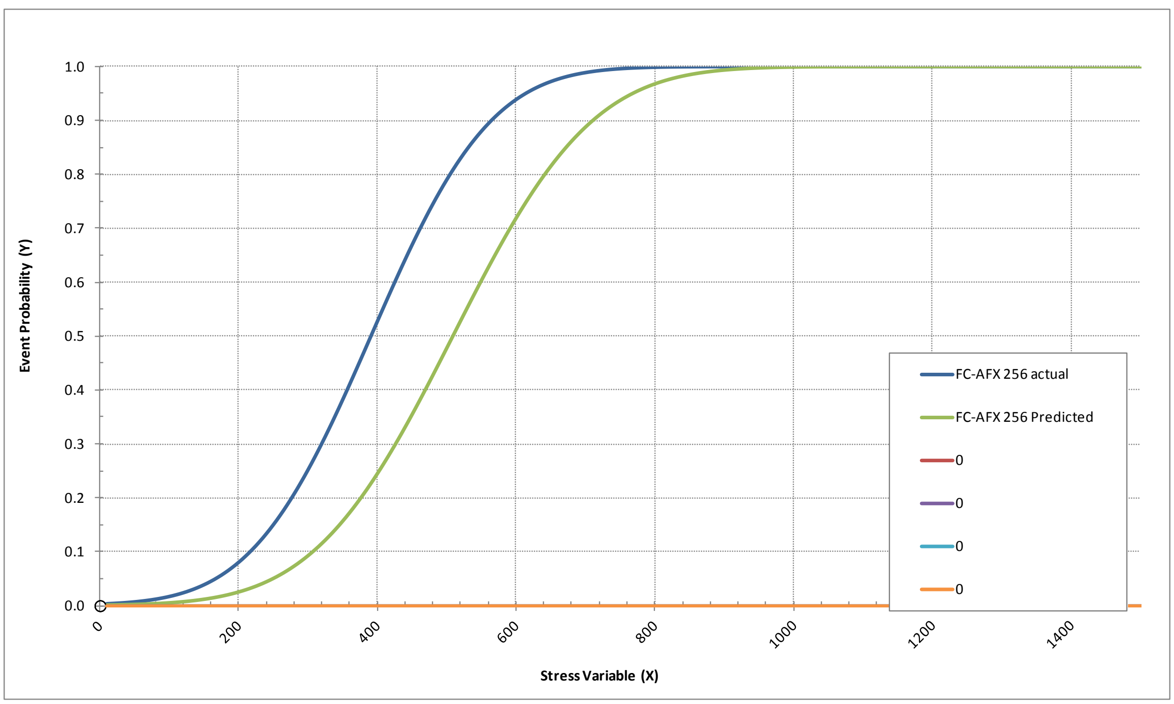


Figure A-4. Probit Regression Curve for AFX-256 sample. Actual experimental data in blue and prediction in green.

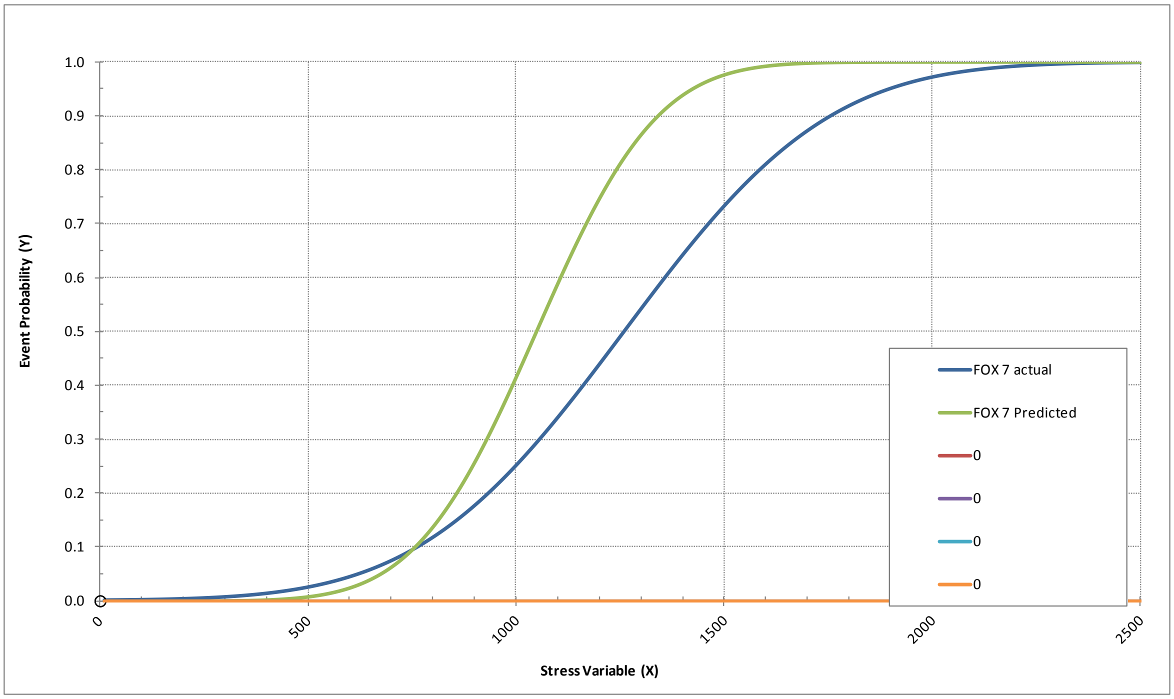


Figure A-5. Probit Regression Curve for FOX-7 sample. Actual experimental data in blue and prediction in green.

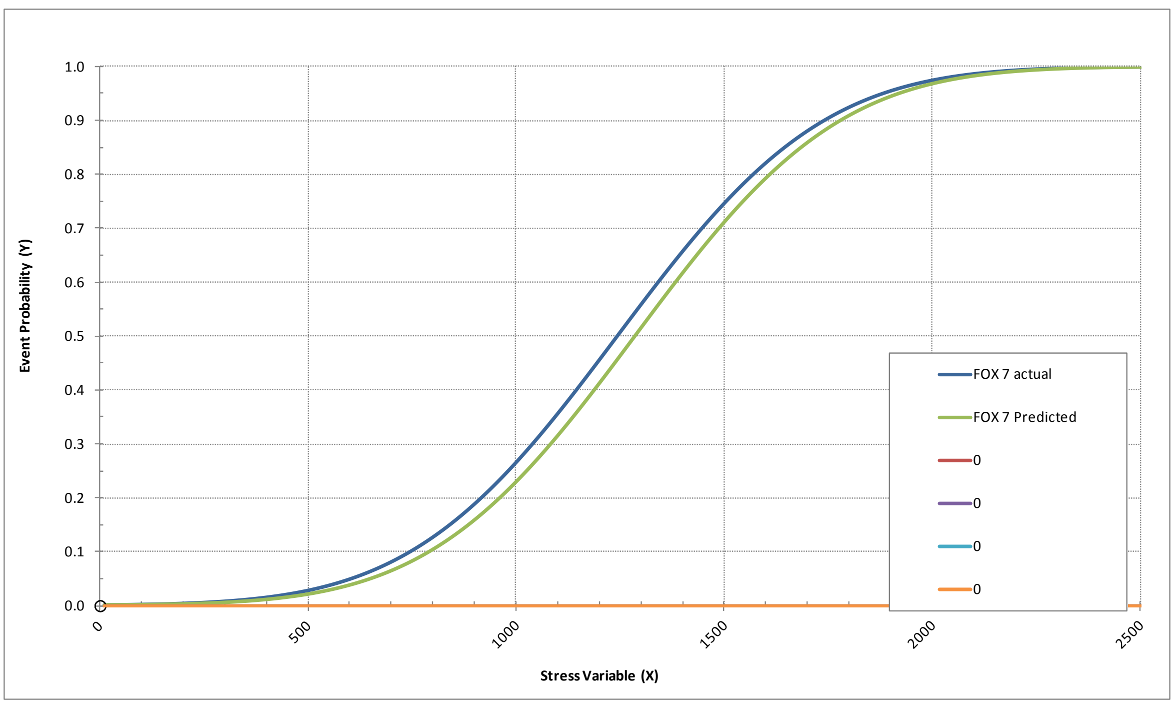


Figure A-6. Probit Regression Curve for FOX-7 sample. Actual experimental data in blue and prediction in green.

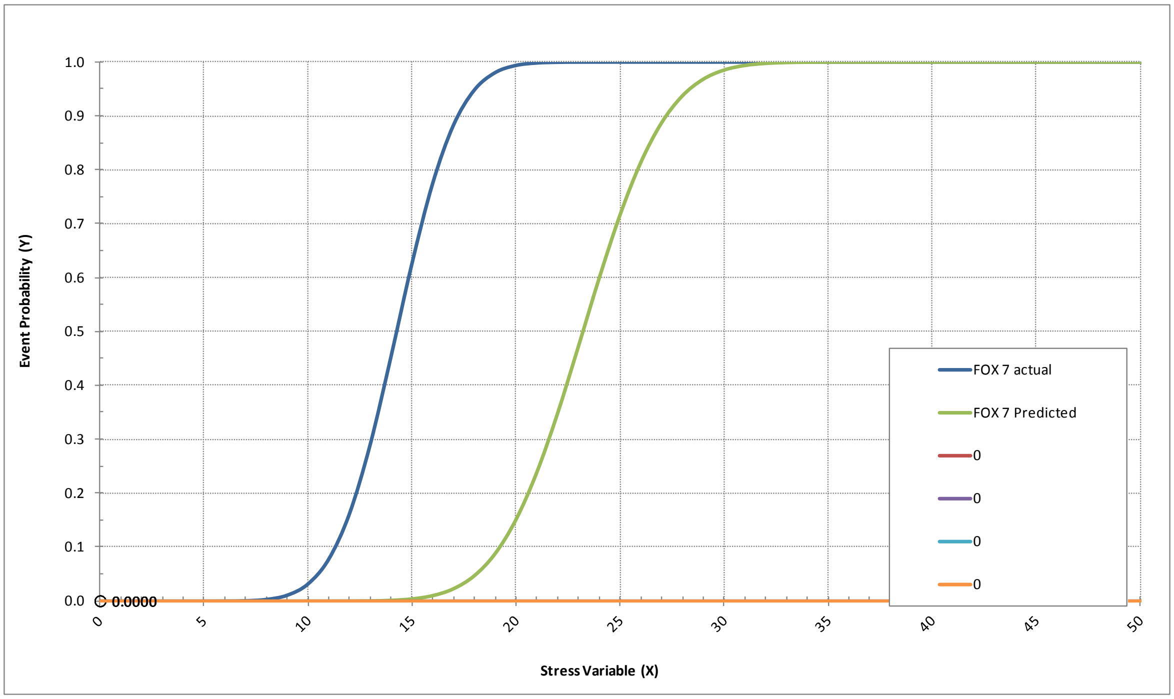


Figure A-7. Probit Regression Curve for FOX-7 sample. Actual experimental data in blue and prediction in green.

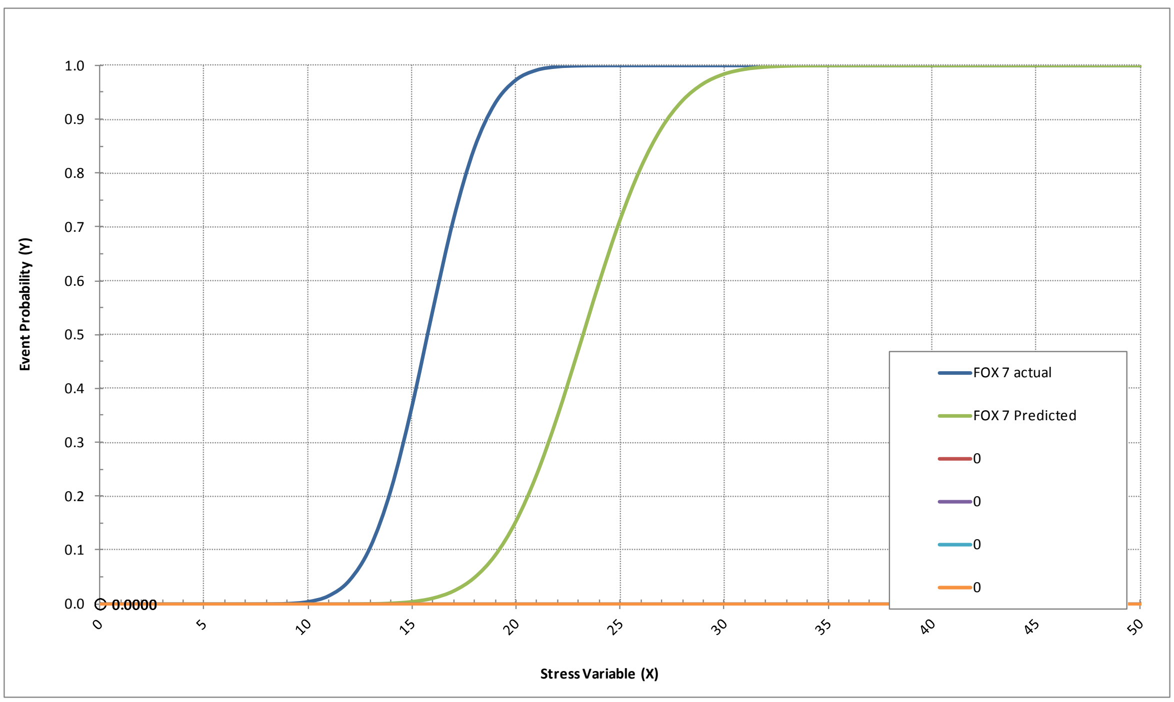


Figure A-8. Probit Regression Curve for FOX-7 sample. Actual experimental data in blue and prediction in green.

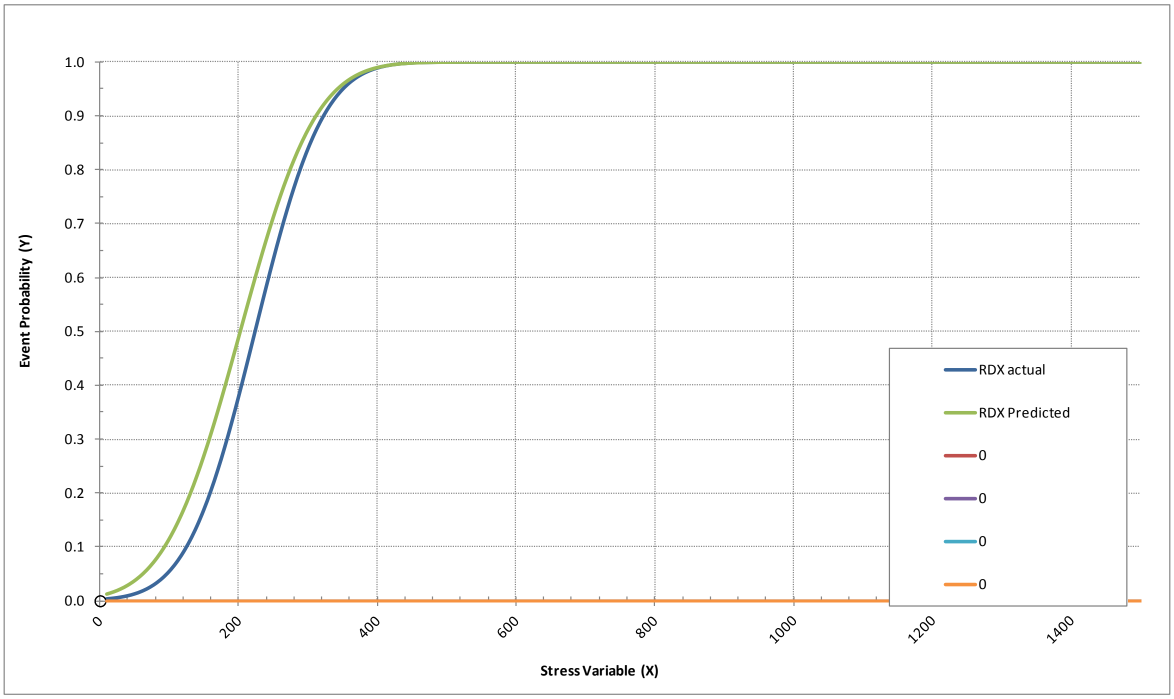


Figure A-9. Probit Regression Curve for RDX sample. Actual experimental data in blue and prediction in green.

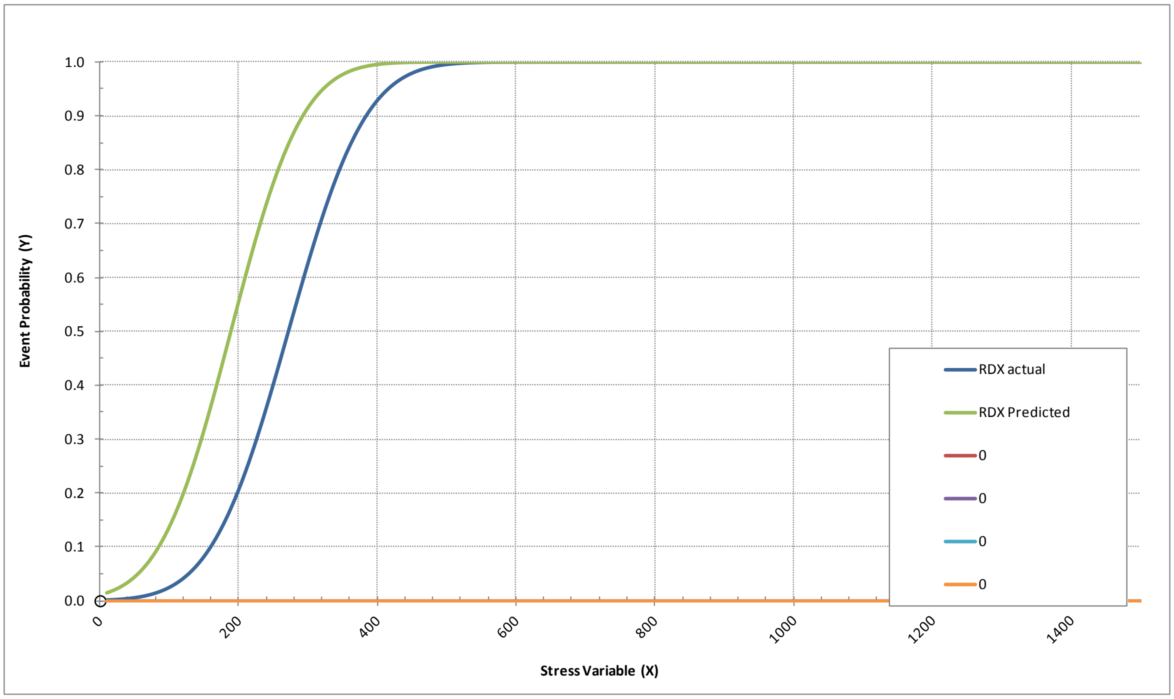


Figure A-10. Probit Regression Curve for RDX sample. Actual experimental data in blue and prediction in green.

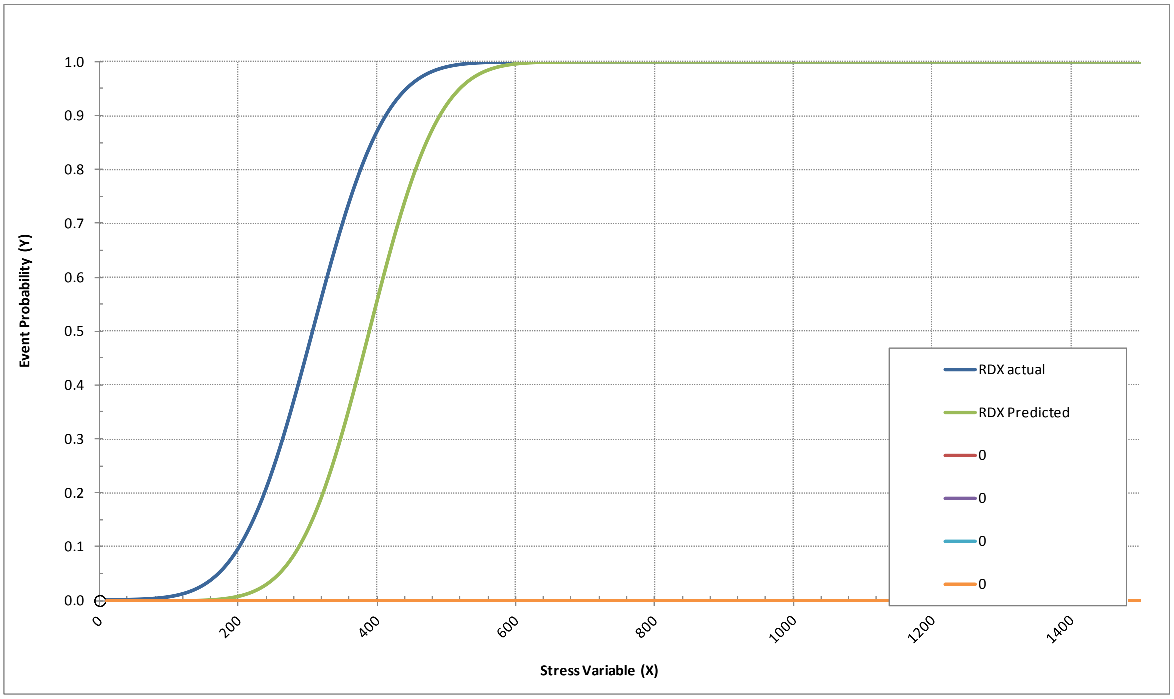


Figure A-11. Probit Regression Curve for RDX sample. Actual experimental data in blue and prediction in green.

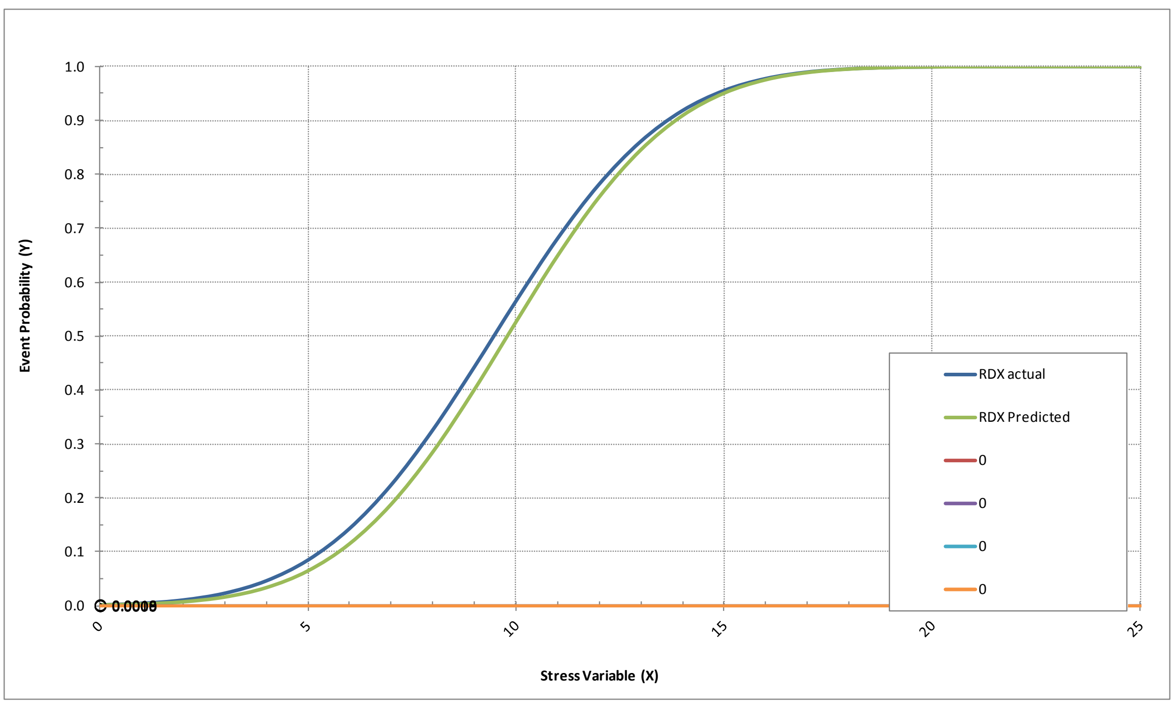


Figure A-12. Probit Regression Curve for RDX sample. Actual experimental data in blue and prediction in green.

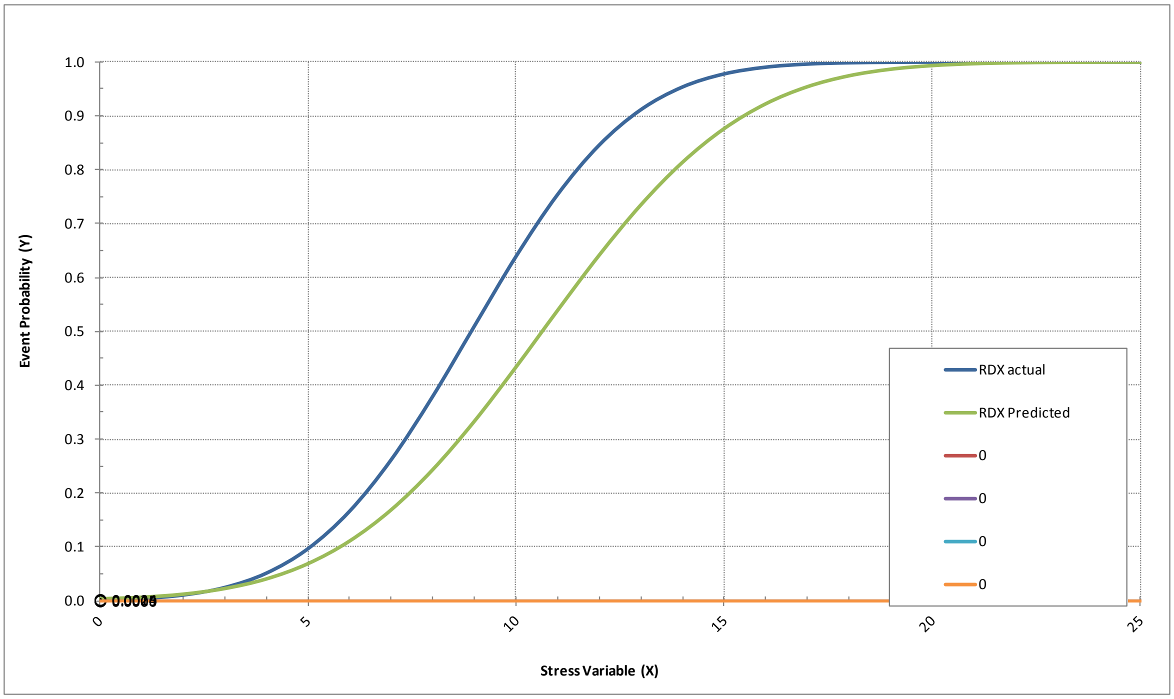


Figure A-13. Probit Regression Curve for RDX sample. Actual experimental data in blue and prediction in green.

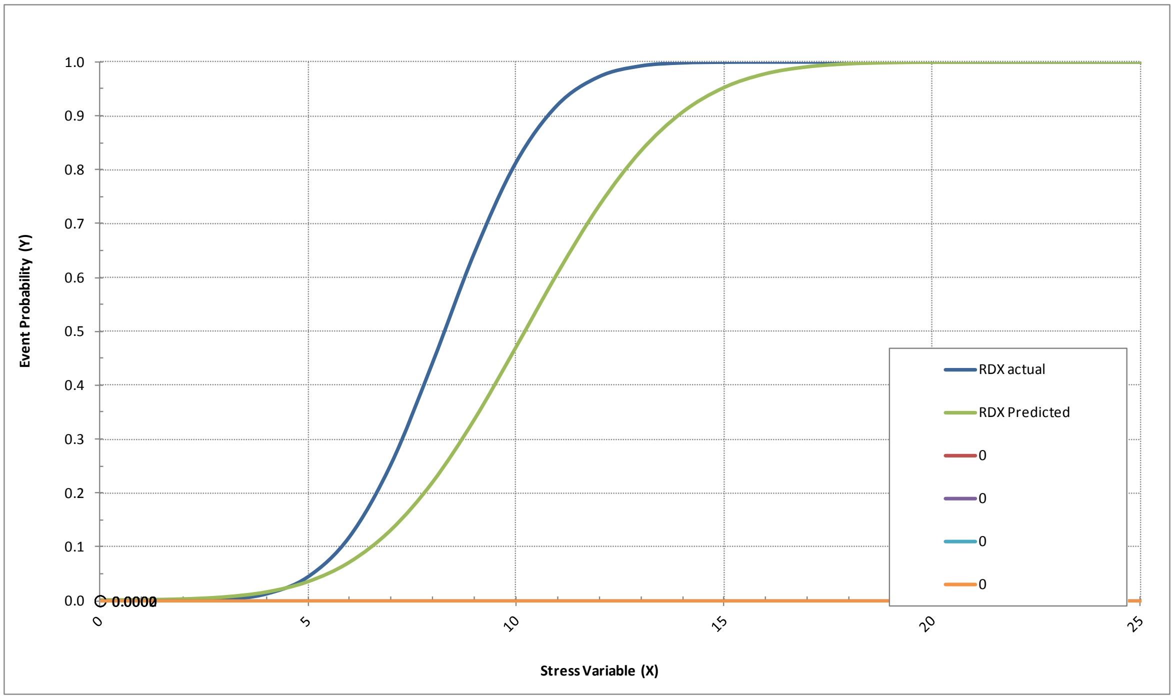


Figure A-14. Probit Regression Curve for RDX sample. Actual experimental data in blue and prediction in green.

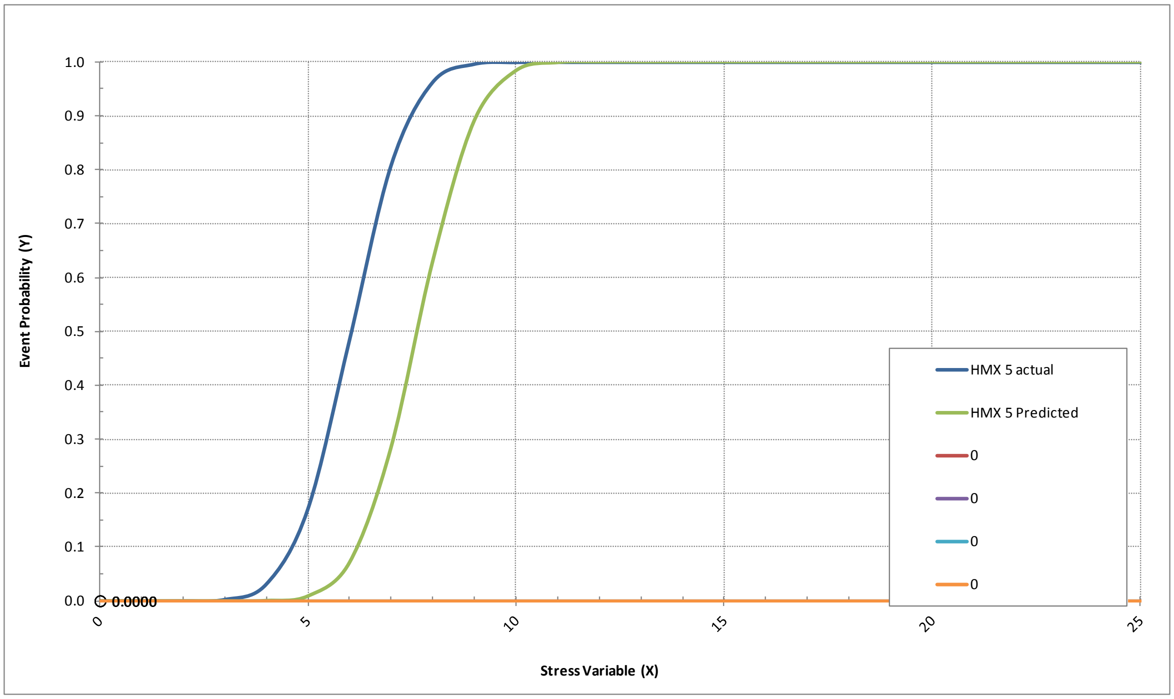


Figure A-15. Probit Regression Curve for HMX sample. Actual experimental data in blue and prediction in green.

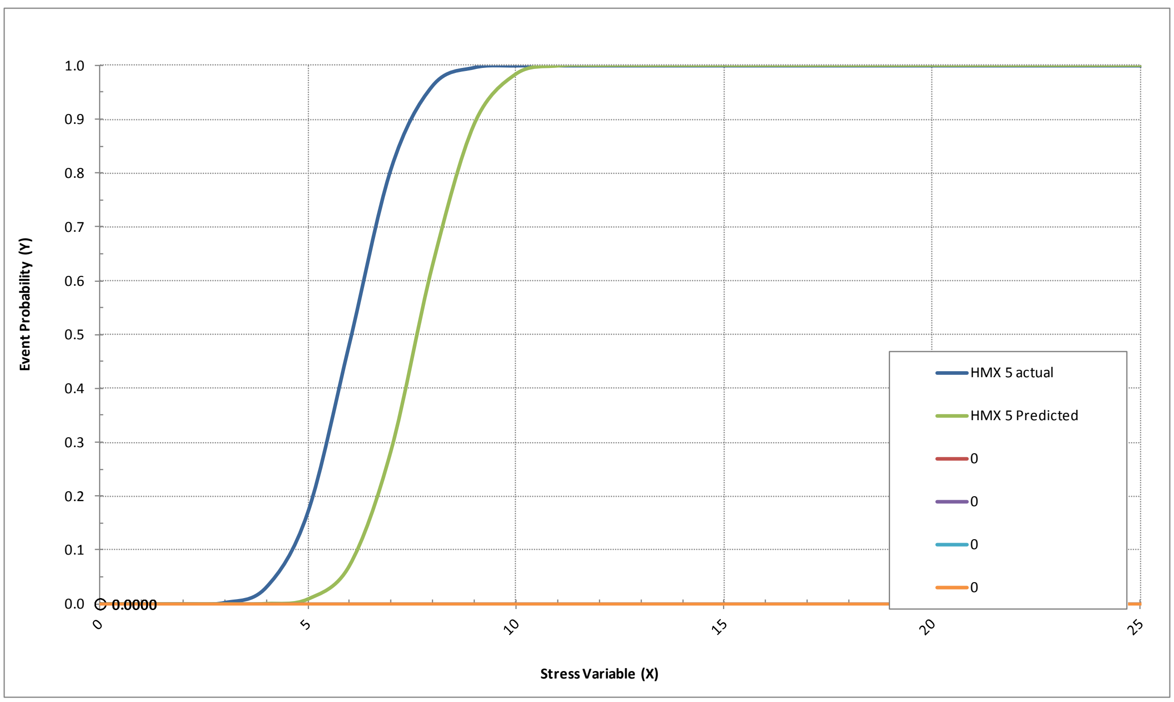


Figure A-16. Probit Regression Curve for HMX sample. Actual experimental data in blue and prediction in green.

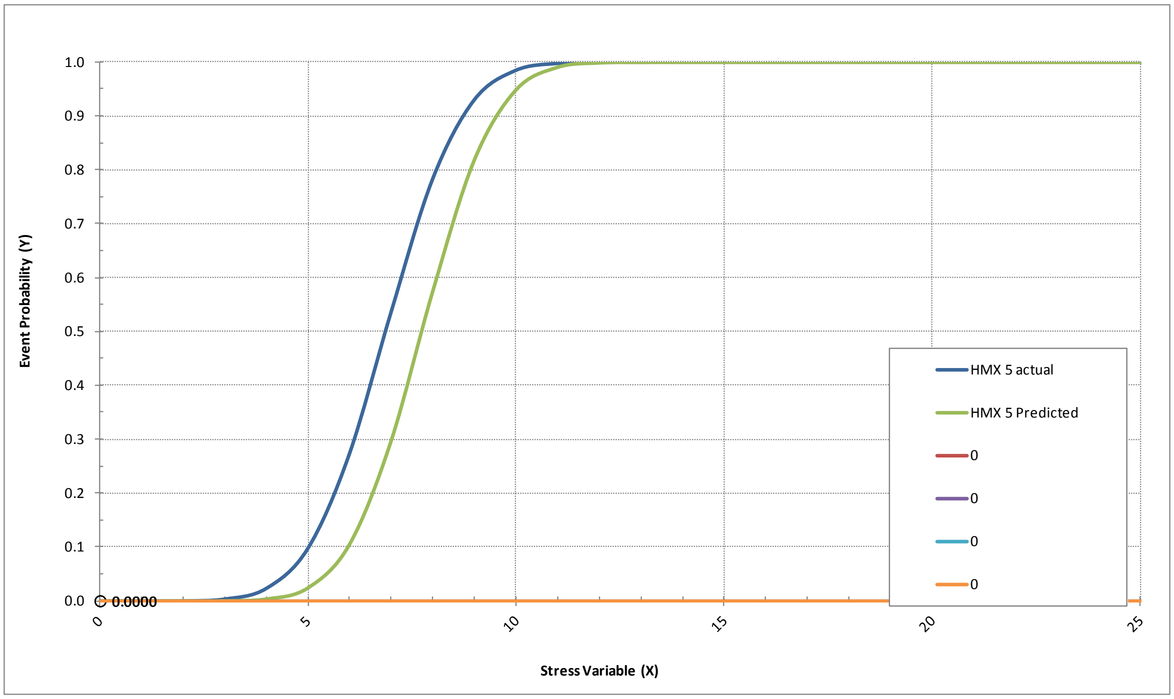


Figure A-17. Probit Regression Curve for HMX sample. Actual experimental data in blue and prediction in green.

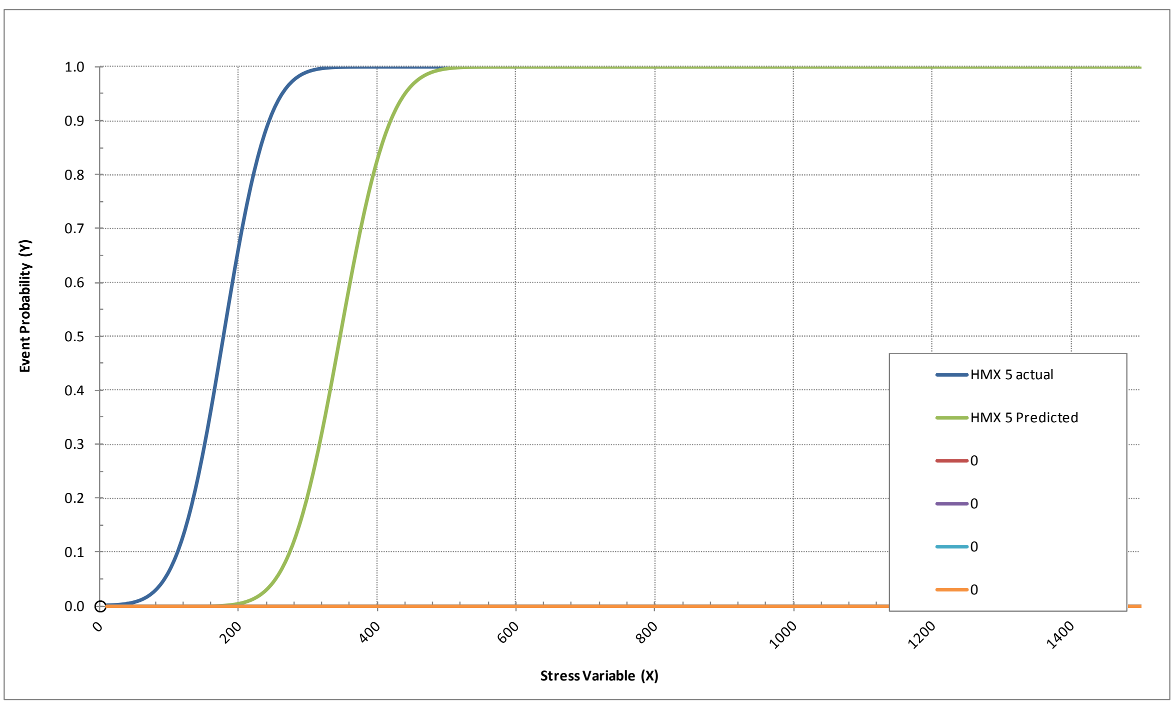


Figure A-18. Probit Regression Curve for HMX sample. Actual experimental data in blue and prediction in green.

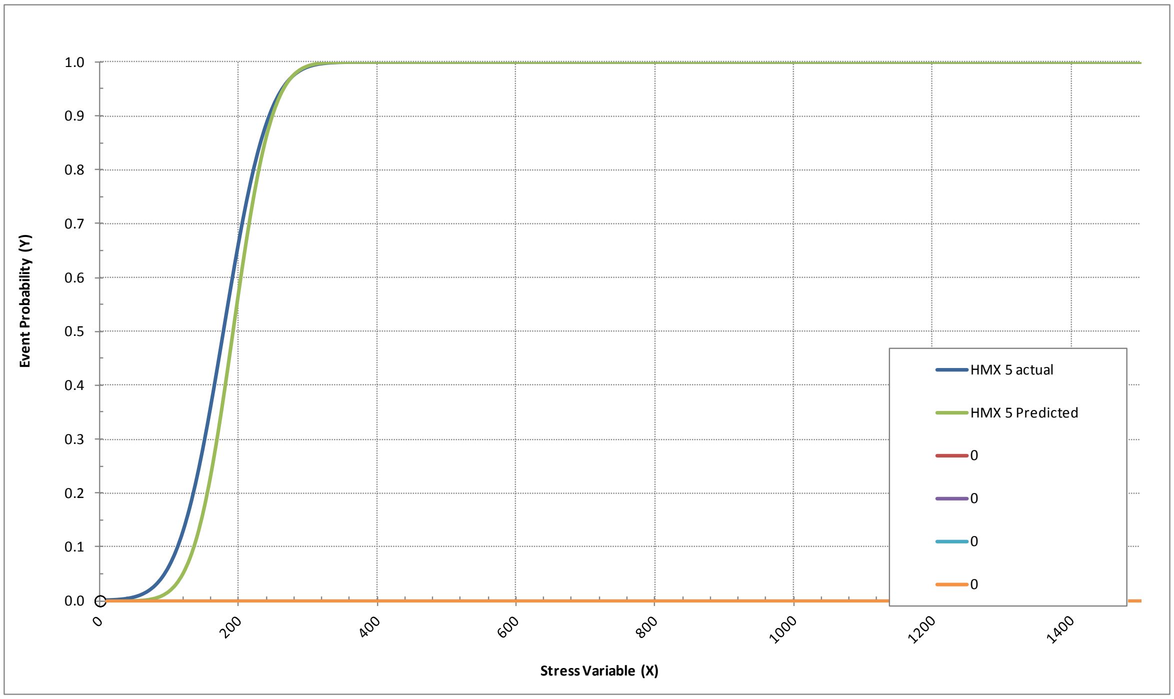


Figure A-19. Probit Regression Curve for HMX sample. Actual experimental data in blue and prediction in green.

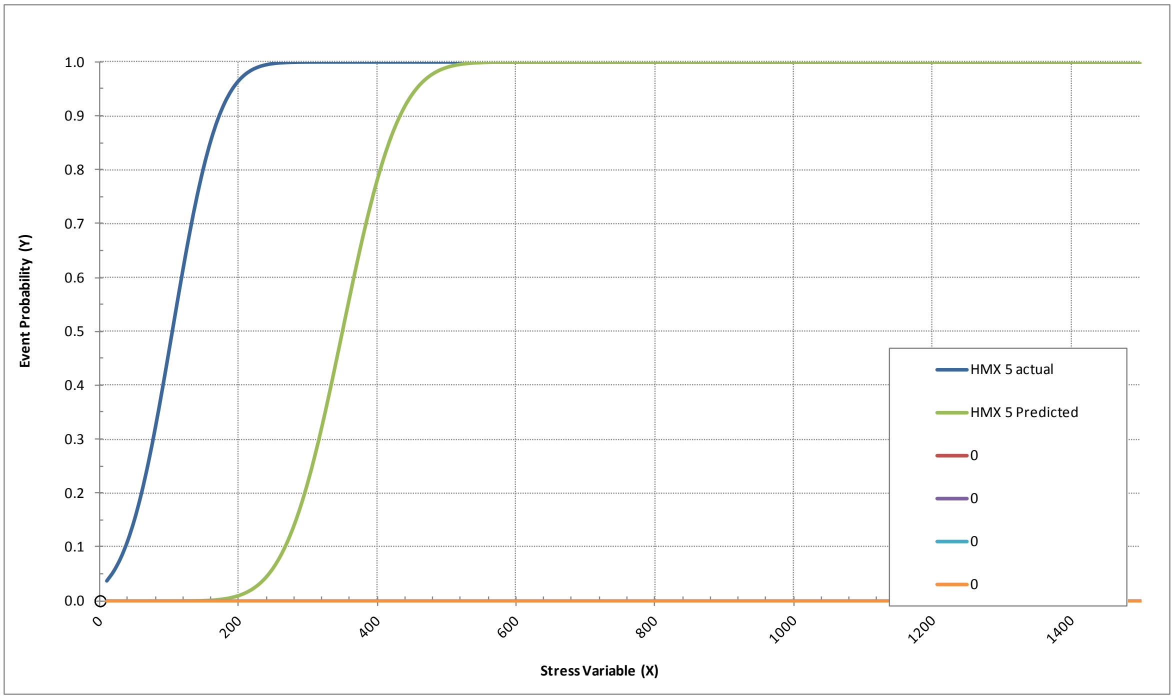


Figure A-20. Probit Regression Curve for HMX sample. Actual experimental data in blue and prediction in green.

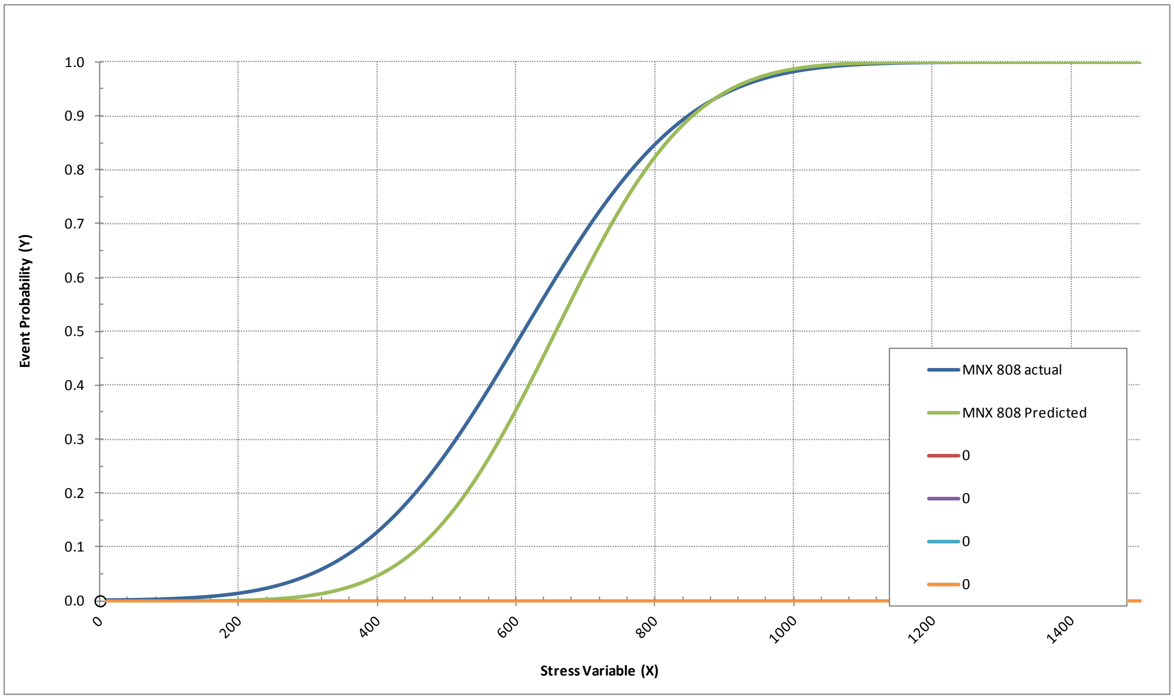


Figure A-21. Probit Regression Curve for MNX-808 sample. Actual experimental data in blue and prediction in green.

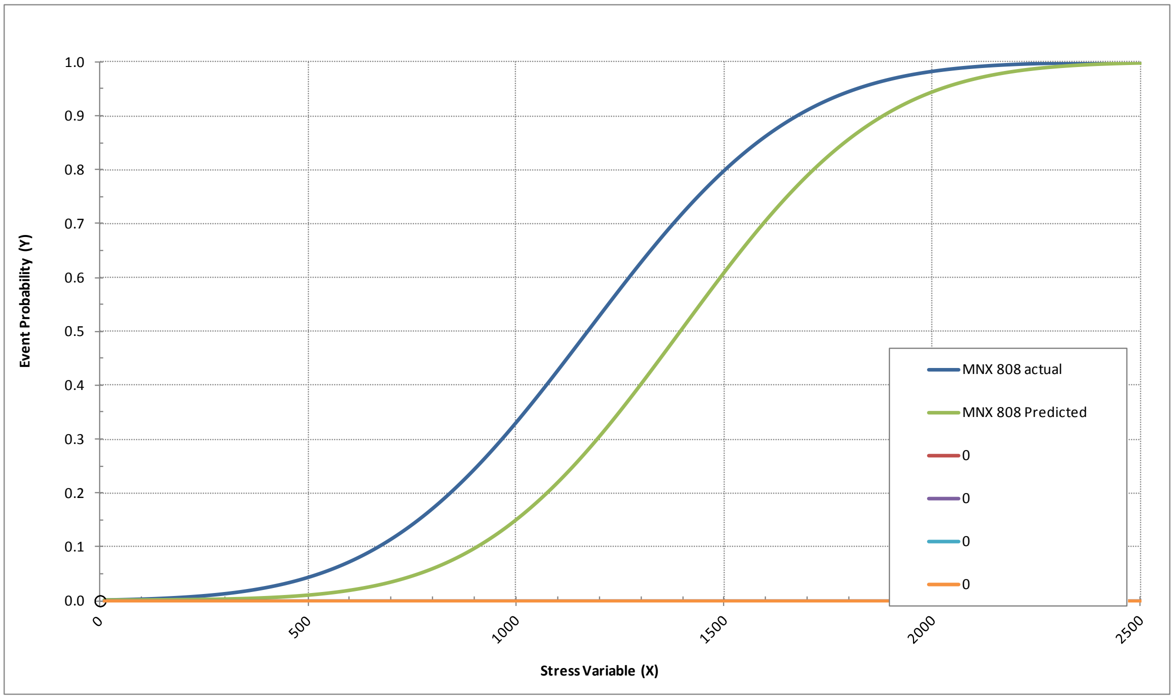


Figure A-22. Probit Regression Curve for MNX-808 sample. Actual experimental data in blue and prediction in green.

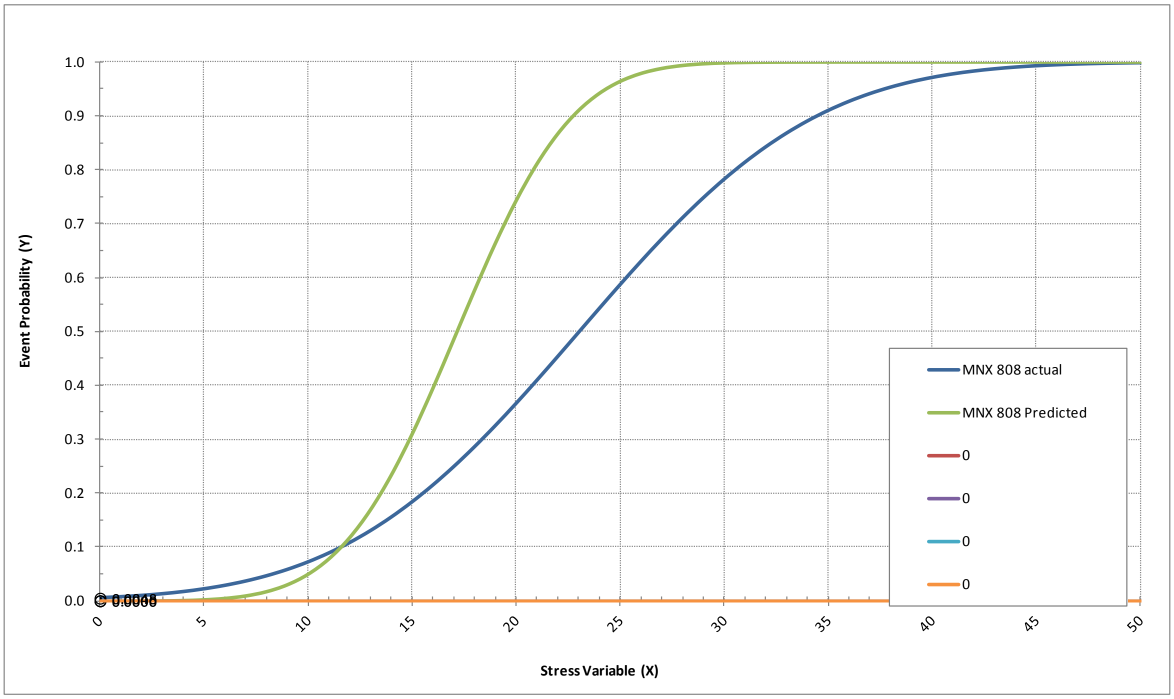


Figure A-23. Probit Regression Curve for MNX-808 sample. Actual experimental data in blue and prediction in green.

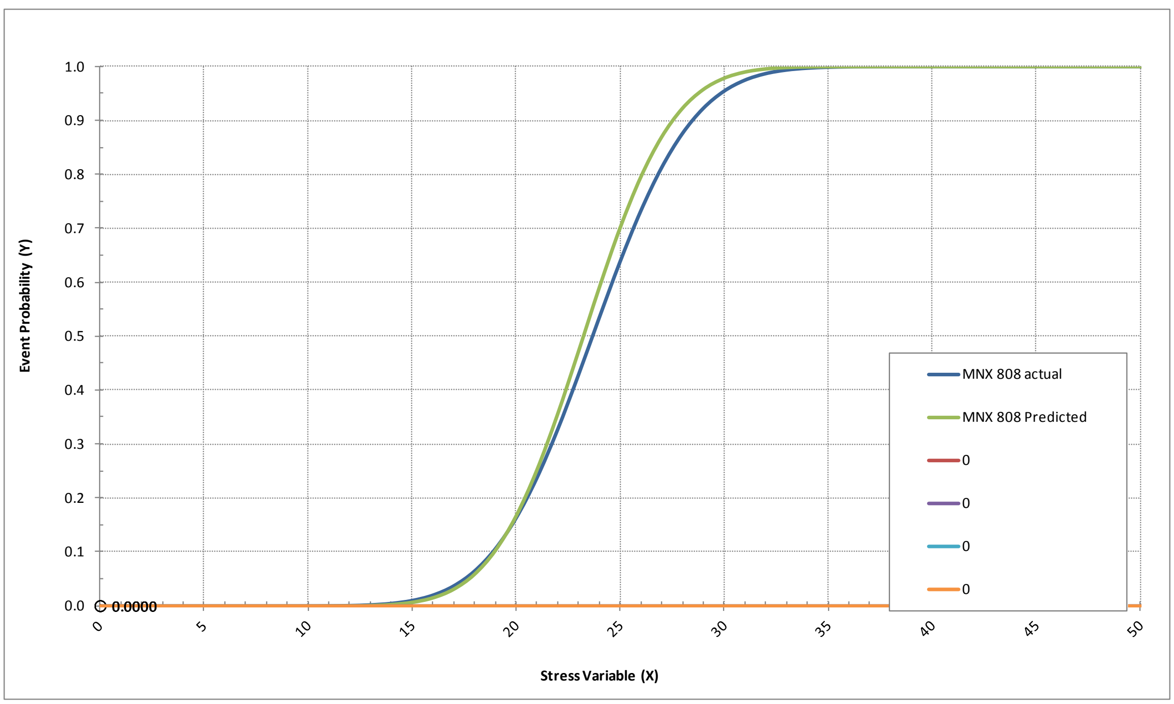


Figure A-24. Probit Regression Curve for MNX-808 sample. Actual experimental data in blue and prediction in green.

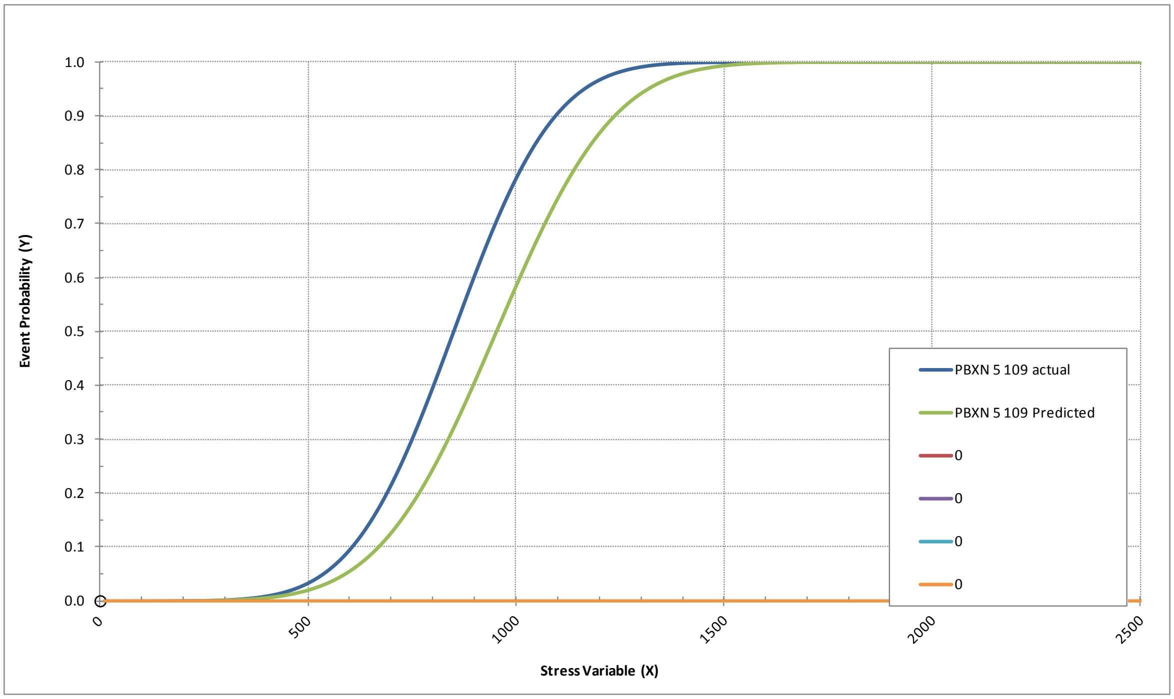


Figure A-25. Probit Regression Curve for PBXN-109 sample. Actual experimental data in blue and prediction in green.

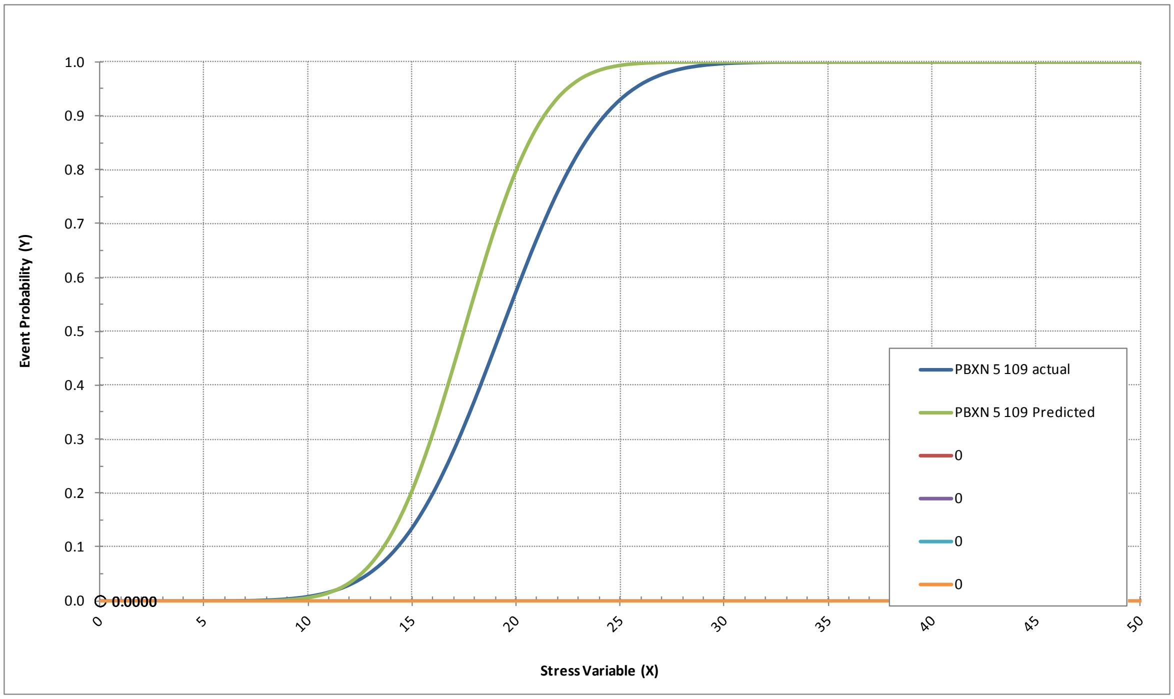


Figure A-26. Probit Regression Curve for PBXN-109 sample. Actual experimental data in blue and prediction in green.

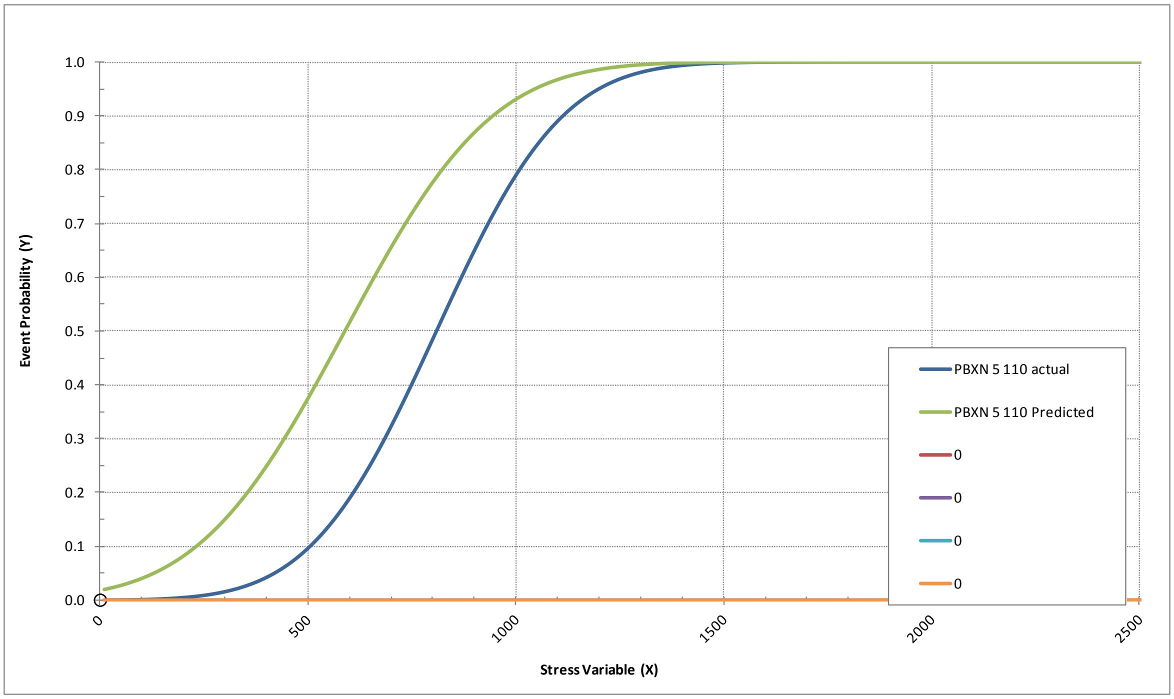


Figure A-27. Probit Regression Curve for PBXN-110 sample. Actual experimental data in blue and prediction in green.

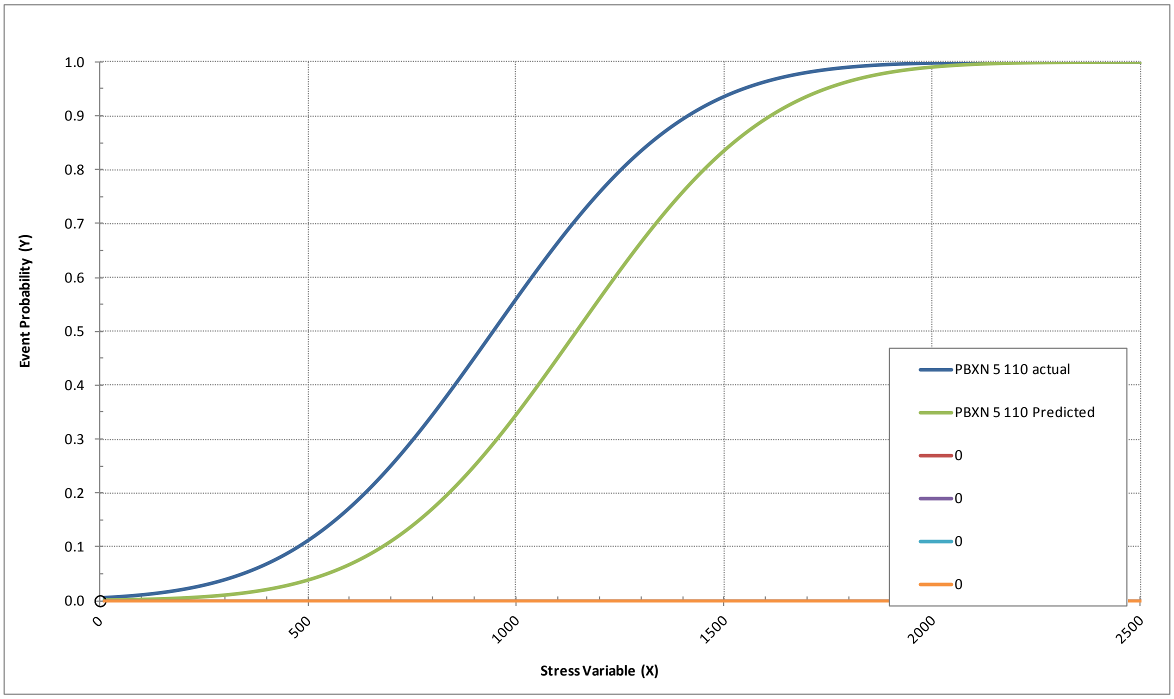


Figure A-28. Probit Regression Curve for PBXN-110 sample. Actual experimental data in blue and prediction in green.

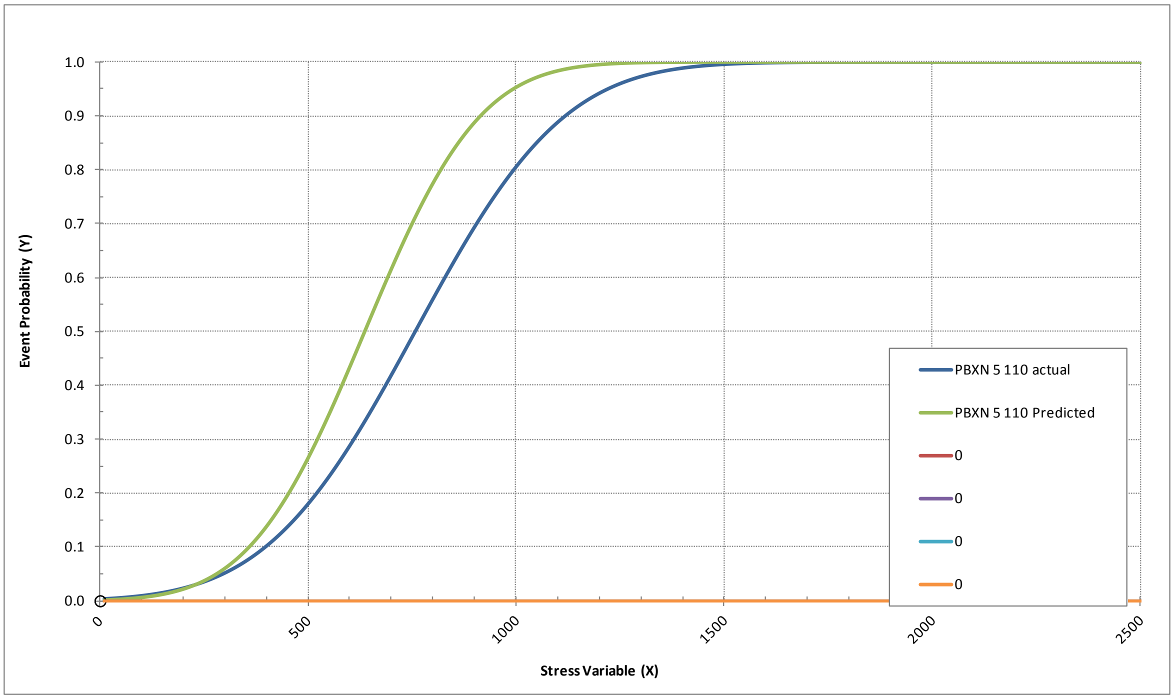


Figure A-29. Probit Regression Curve for PBXN-110 sample. Actual experimental data in blue and prediction in green.

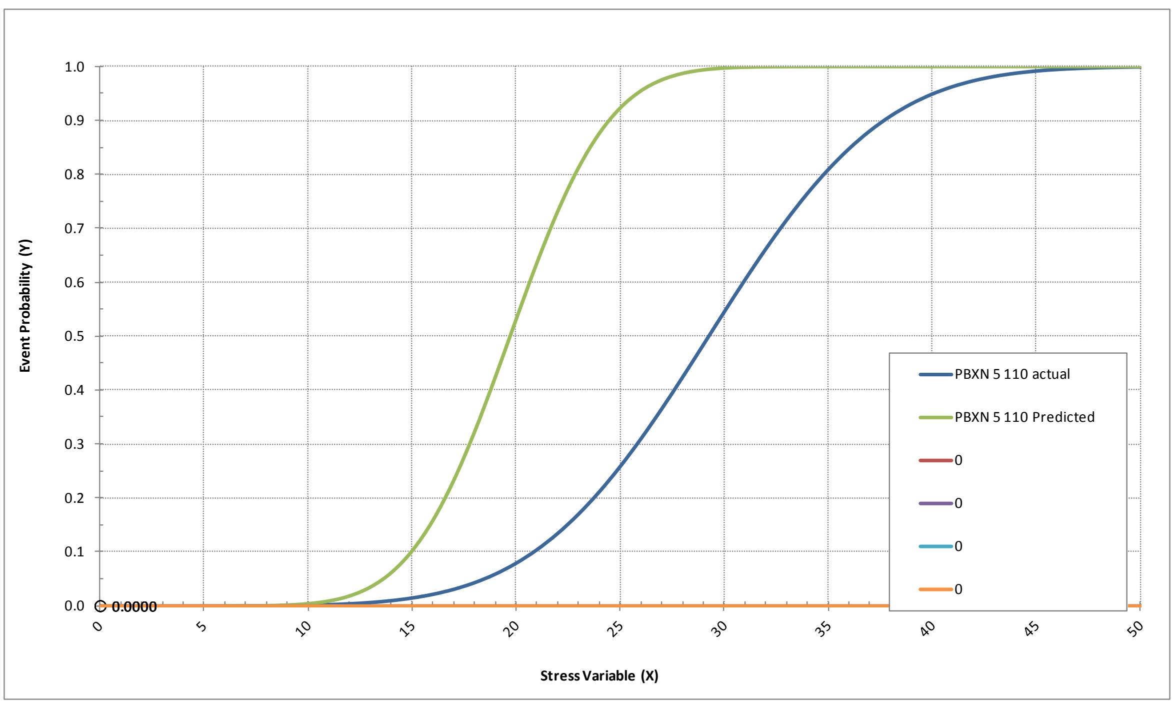


Figure A-30. Probit Regression Curve for PBXN-110 sample. Actual experimental data in blue and prediction in green.

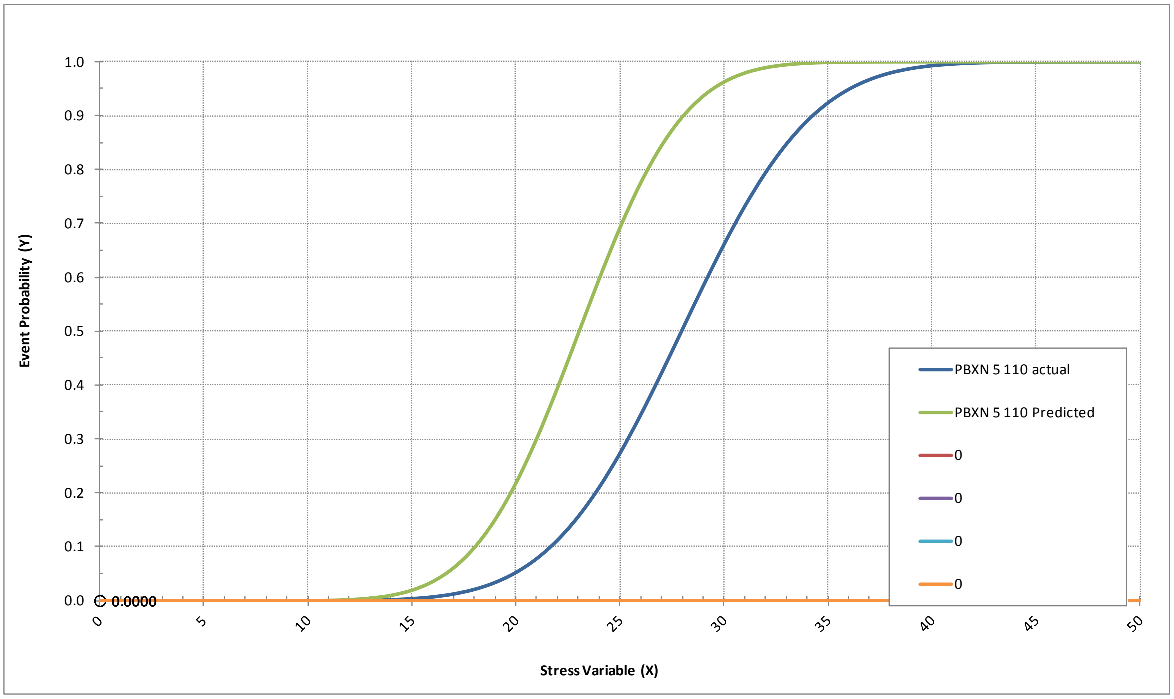


Figure A-31. Probit Regression Curve for PBXN-110 sample. Actual experimental data in blue and prediction in green.

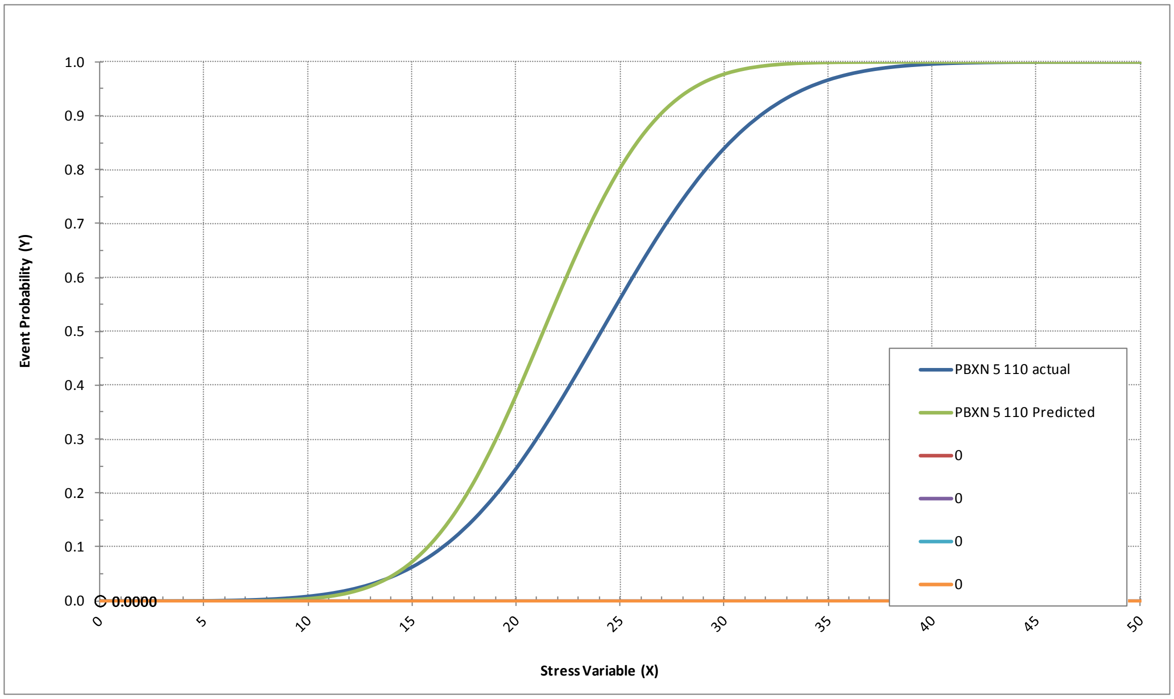


Figure A-32. Probit Regression Curve for PBXN-110 sample. Actual experimental data in blue and prediction in green.

	kg	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go	Summary No-Go
BAM	36.0													0	0
	32.4													0	0
	28.8													0	0
	25.2													0	0
	24.0	|												0	0
	21.6													0	0
	19.2													0	0
	18.0													0	0
	16.8													0	0
	16.0	|												0	0
	14.4	|						|	|	|	|	|		0	0
	12.8	|						|	|	|	|	|		0	0
	12.0	|						O						0	0
	11.2	|						O						0	0
	10.8	|						O						0	0
	9.6	|						O						0	0
	8.4	O	O	O	O	O								0	0
	8.0	O	O	O	O									0	0
	7.2													0	0
	6.4													0	0
	6.0													0	0
	5.6													0	0
	5.4													0	0
	4.8													0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

	psi	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6
	1995	|						|	|	|	|	|	|
	1585	|						|	|	O			
ABL	1260	O	|					|	O				
	1000	O	O	O	O	O							
	800	O	O	O	O	O							
	660												
	560												
	420												
	370												
	320												
	240												
	180												
	130												
	100												
	50												

Sample AFX 196
Date 12 May 2014
Temp 18.1
RH 16%

Overview

Down
1 No-fire searc
2 No-fire locati
3 No-fire confi
Up
4 All-fire searcl
5 All-fire locati
6 All-fire confir
7 Mixed-result

Figure A-33. Raw data sheet for AFX-196

	kg	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go	Summary No-Go
BAM	36.0													0	0
	32.4													0	0
	28.8													0	0
	25.2													0	0
	24.0													0	0
	21.6													0	0
	19.2													0	0
	18.0													0	0
	16.8													0	0
	16.0							1	1	1	1	1		0	0
	14.4	1						0	0	0	0	0		0	0
	12.8	0	0	1				[illegible]	1	1	0			0	0
	12.0	0	0	0	0	0								0	0
	11.2	0	0	0	0	0								0	0
	10.8													0	0
	9.6													0	0
	8.4													0	0
	8.0													0	0
	7.2													0	0
	6.4													0	0
	6.0													0	0
	5.6													0	0
	5.4													0	0
	4.8													0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

↑ Mostly burn marks on plate
↳ a few sound, no visuals at all

	psi	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6
ABL	1995	1											
	1585	0	1					1	1	1	1	1	
	1260	1						1	1	1	1	1	
	1000	1						1	0				
	800	0	0	1				0					
	660	0	0	0	0	0							
	560	0	0	0	0	0							
	420												
	370												
	320												
	240												
	180												
	130												
	100												
	50												

Sample: AFX 196
Date: 6 May 2014
Temp: 19.0
RH: 42

↖ Smoke or smell →

Overview

Down:
1 No-fire searc
2 No-fire locati
3 No-fire confi

Up:
4 All-fire searcl
5 All-fire locati
6 All-fire confir
7 Mixed-result

Figure A-34. Raw data sheet for AFX-196

	kg	Down						Up						Summary	
		1	2	3	4	5	6	1	2	3	4	5	6	Go	No-Go
	36.0													0	0
	32.4													0	0
	28.8													0	0
	25.2													0	0
	24.0	1–mark												0	0
	21.6	1						1m	1m	1s	1m	1m		0	0
	19.2	O	1s					1m	1m	1m	1m	1s		0	0
	18.0	O	1m					1m	1m	O				0	0
	16.8	1m						O						0	0
	16.0	1m						O						0	0
	14.4	1s						O						0	0
	12.8	1s						O						0	0
	12.0	O	O	O	O	O								0	0
	11.2	O	O	O	O	O								0	0
BAM	10.8													0	0
	9.6													0	0
	8.4													0	0
	8.0													0	0
	7.2													0	0
	6.4													0	0
	6.0													0	0
	5.6													0	0
	5.4													0	0
	4.8													0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

	psi	Down						Up						Sum
		1	2	3	4	5	6	1	2	3	4	5	6	Go
	800	O	O	O	O	O								0
	660	O	O	O	O	O								0
	560													0
	420													0
ABL	370													0
	320													0
	240													0
	180													0
	130													0
	100													0
	50													0

Sample AFX 196
Date 26 Feb 14
Temp 17.8
RH 52%

Overview

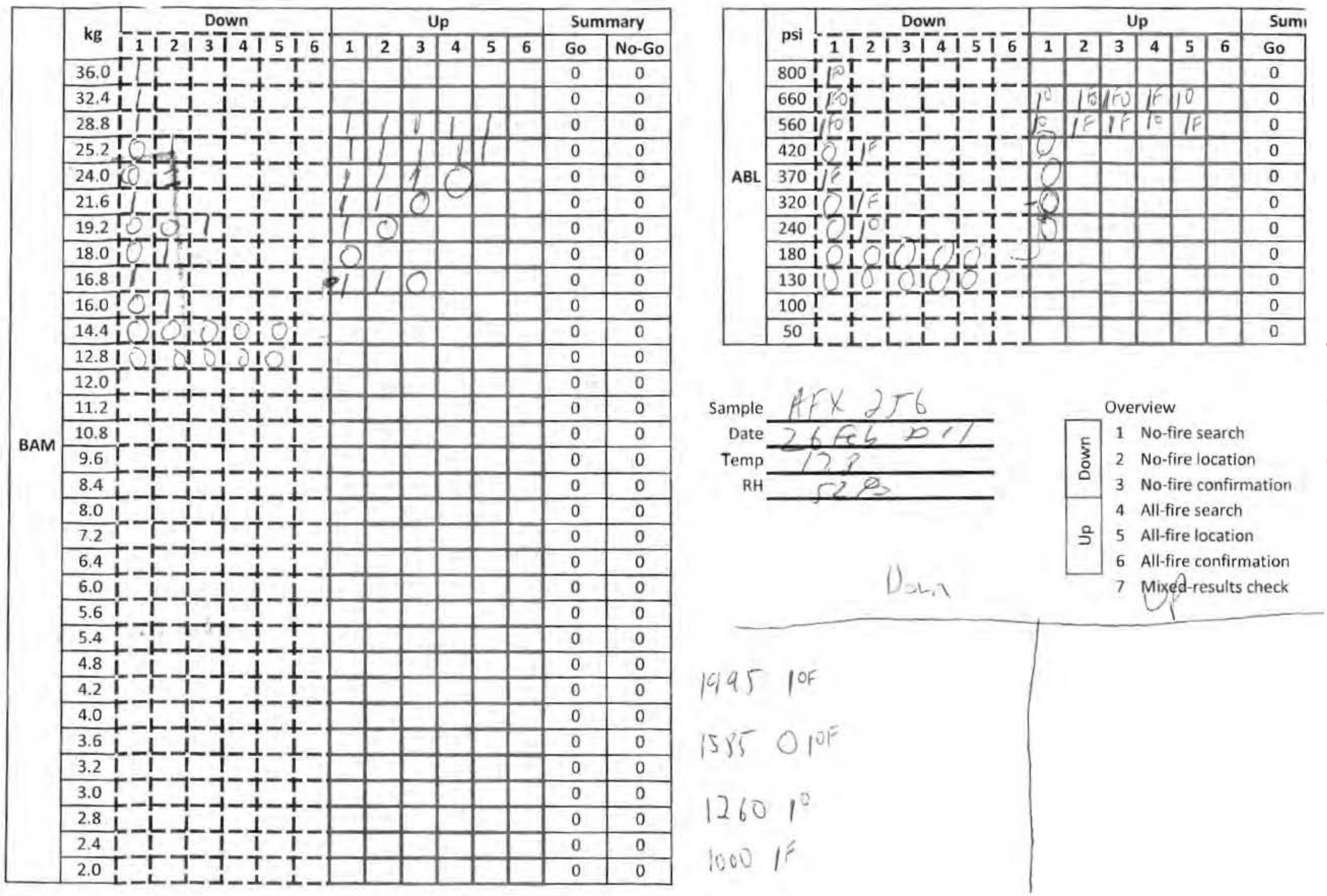
Down
1 No-fire search
2 No-fire location
3 No-fire confirmation

Up
4 All-fire search
5 All-fire location
6 All-fire confirmation
7 Mixed-results check

Down	Up
1995 1 odor	
1585 1 odor	11111
1260 1 odor	11111
1000 0 1 odor	O

Note: All on ODor!/Smoke

Figure A-35. Raw data sheet for AFX-196



BAM	kg	Down 1	2	3	4	5	6	Up 1	2	3	4	5	6	Summary Go	No-Go
	36.0													0	0
	32.4													0	0
	28.8													0	0
	25.2													0	0
	24.0													0	0
	21.6													0	0
	19.2													0	0
	18.0													0	0
	16.8													0	0
	16.0													0	0
	14.4													0	0
	12.8													0	0
	12.0													0	0
	11.2													0	0
	10.8													0	0
	9.6													0	0
	8.4													0	0
	8.0													0	0
	7.2													0	0
	6.4													0	0
	6.0													0	0
	5.6													0	0
	5.4													0	0
	4.8													0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

ABL	psi	Down 1	2	3	4	5	6	Up 1	2	3	4	5	6	Sum Go
	800													0
	660													0
	560													0
	420													0
	370													0
	320													0
	240													0
	180													0
	130													0
	100													0
	50													0

Sample AFX 256
Date 26 Feb 2011
Temp 72 F
RH 52%

Overview

Down	1	No-fire search
	2	No-fire location
	3	No-fire confirmation
Up	4	All-fire search
	5	All-fire location
	6	All-fire confirmation
	7	Mixed-results check

Down Up

1495 1OF
1585 O 1OF
1260 1O
1000 1F

Figure A-36. Raw data sheet for AFX-256

BAM	kg	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go	Summary No-Go
	36.0													0	0
	32.4													0	0
	28.8													0	0
	25.2													0	0
	24.0													0	0
	21.6													0	0
	19.2							\	|	/	|	|		0	0
	18.0							|	|	/	|	|		0	0
	16.8							|	|	O				0	0
	16.0	|						O						0	0
	14.4	|						|	O					0	0
	12.8	/						O						0	0
	12.0	O	|					O						0	0
	11.2	O	O	O	O	O								0	0
	10.8	O	O	O	O	O								0	0
	9.6													0	0
	8.4													0	0
	8.0													0	0
	7.2													0	0
	6.4													0	0
	6.0													0	0
	5.6													0	0
	5.4													0	0
	4.8													0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

"Goes" are mostly brown burn streaks on plate. Rarely sound.

ABL	psi	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6
	1995	|						|	|	\	|	|	|
	1585	|						|	O				
	1260	O	|					O					
	1000	|						O					
	800	O	|					O					
	660	O	O	O	O	O							
	560	O	O	O	O	O							
	420												
	370												
	320												
	240												
	180												
	130												
	100												
	50												

Sample: FOX 7 Fine
Date: 8 May 2014
Temp: 19 C
RH: 45

Overview

Down	1	No-fire searc
	2	No-fire locati
	3	No-fire confi
Up	4	All-fire searc
	5	All-fire locati
	6	All-fire confir
	7	Mixed-result

Figure A-37. Raw data sheet for FOX-7

	kg	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go	Summary No-Go
BAM	36.0													0	0
	32.4													0	0
	28.8							/	/	/	/	/		0	0
	25.2							/	/	/	/	/		0	0
	24.0	O	O	O	/	/								0	0
	21.6	O	O	O	O	O	/	O	O					0	0
	19.2	O	O	O	/	O								0	0
	18.0	O	O	/	/	O								0	0
	16.8	O	O	O	O	O								0	0
	16.0													0	0
	14.4													0	0
	12.8													0	0
	12.0													0	0
	11.2													0	0
	10.8													0	0
	9.6													0	0
	8.4													0	0
	8.0													0	0
	7.2													0	0
	6.4													0	0
	6.0													0	0
	5.6													0	0
	5.4													0	0
	4.8													0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

	psi	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summ Go
ABL	800													0
	660													0
	560													0
	420													0
	370													0
	320													0
	240													0
	180													0
	130													0
	100													0
	50													0

Sample Fox 7 Fine
Date 11 Feb 2021
Temp 17 C
RH 60

Overview
Down
1 No-fire search
2 No-fire location
3 No-fire confirmation
Up
4 All-fire search
5 All-fire location
6 All-fire confirmation
7 Mixed-results check

	nogo	go
1300	5	2
1500	4	1
[illegible]	|||||||||||||||	
1955	111	11

Figure A-38. Raw data sheet for FOX-7

	kg	Down						Up						Summary	
		1	2	3	4	5	6	1	2	3	4	5	6	Go	No-Go
BAM	36.0	0	0	1	1									0	0
	32.4													0	0
	28.8													0	0
	25.2													0	0
	24.0	0	0											0	0
	21.6													0	0
	19.2													0	0
	18.0													0	0
	16.8													0	0
	16.0													0	0
	14.4													0	0
	12.8													0	0
	12.0													0	0
	11.2													0	0
	10.8													0	0
	9.6													0	0
	8.4													0	0
	8.0													0	0
	7.2													0	0
	6.4													0	0
	6.0													0	0
	5.6													0	0
	5.4													0	0
	4.8													0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

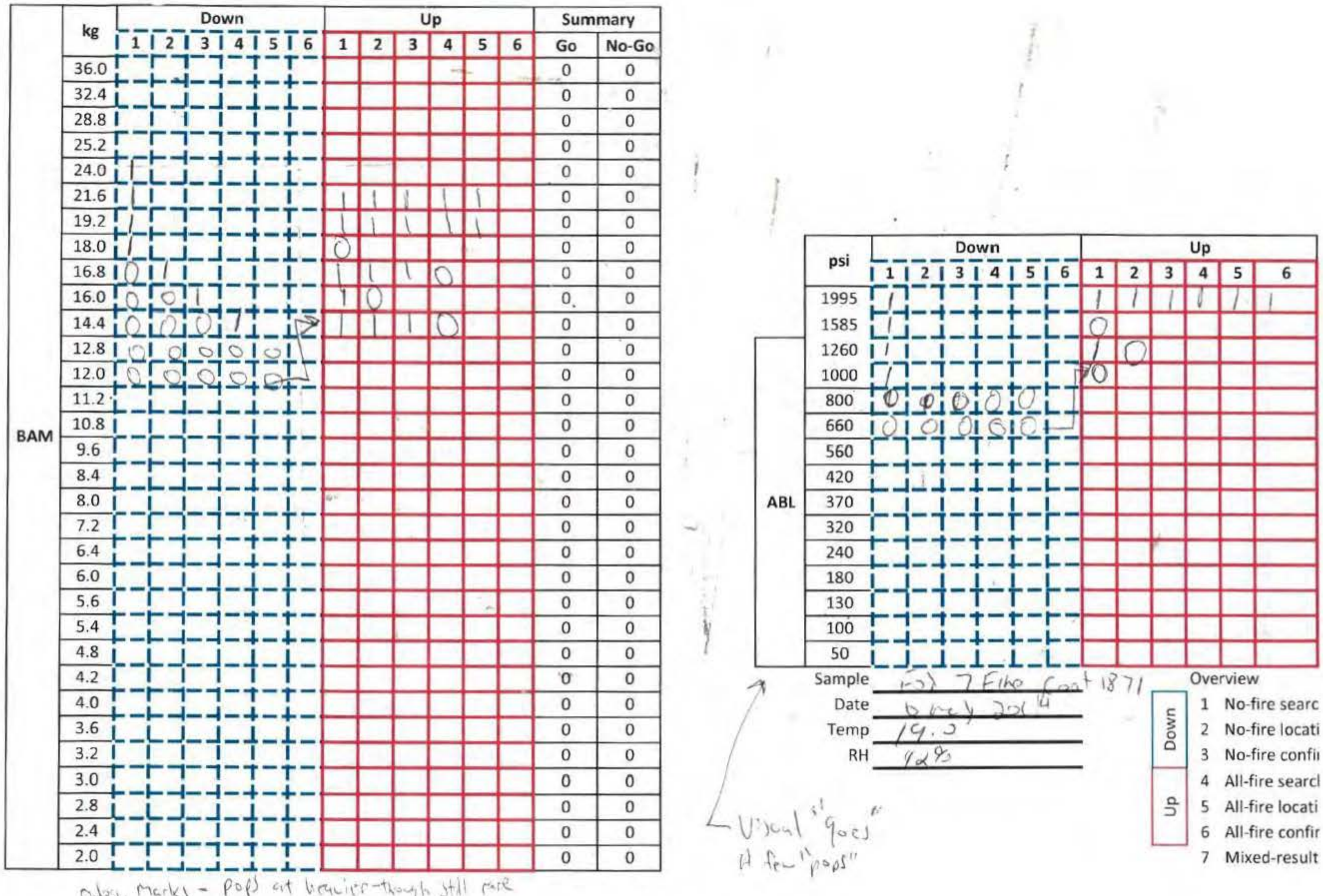
	psi	Down						Up						Sum
		1	2	3	4	5	6	1	2	3	4	5	6	Go
	1000	0	0	0										
ABL	800	0	0	0	0									0
	660													0
	560													0
	420													0
	370													0
	320													0
	240													0
	180													0
	130													0
	100													0
	50													0

Sample Fox 7
Date 10 FEB 14
Temp 15 C
RH 68%

Overview

Down	1	No-fire search
	2	No-fire location
	3	No-fire confirmation
Up	4	All-fire search
	5	All-fire location
	6	All-fire confirmation
	7	Mixed-results check

Figure A-39. Raw data sheet for FOX-7



	kg	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go	Summary No-Go
BAM	36.0													0	0
	32.4													0	0
	28.8													0	0
	25.2													0	0
	24.0	|												0	0
	21.6	|						|	|	|	|	|		0	0
	19.2	|						|	|	|		|		0	0
	18.0	|						O						0	0
	16.8	O	|					|	|	|	O			0	0
	16.0	O	O	|				|	O					0	0
	14.4	O	O	O	|			|	|	|	O			0	0
	12.8	O	O	O	O	O								0	0
	12.0	O	O	O	O	O								0	0
	11.2													0	0
	10.8													0	0
	9.6													0	0
	8.4													0	0
	8.0													0	0
	7.2													0	0
	6.4													0	0
	6.0													0	0
	5.6													0	0
	5.4													0	0
	4.8													0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

Odors, Marks - Pops at heavier - though still rare

	psi	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6
ABL	1995	|						|	|	|	|	|	|
	1585	|						O					
	1260	|						|	O				
	1000	|						O					
	800	O	O	O	O	O							
	660	O	O	O	O	O							
	560												
	420												
	370												
	320												
	240												
	180												
	130												
	100												
	50												

Sample FOX 7 Fine Coat 1871
Date 6 Feb 2014
Temp 19.3
RH 42%

Visual "goes"
A few "pops"

Overview
Down
1 No-fire searc
2 No-fire locati
3 No-fire confi
Up
4 All-fire searcl
5 All-fire locati
6 All-fire confir
7 Mixed-result

Figure A-40. Raw data sheet for FOX-7

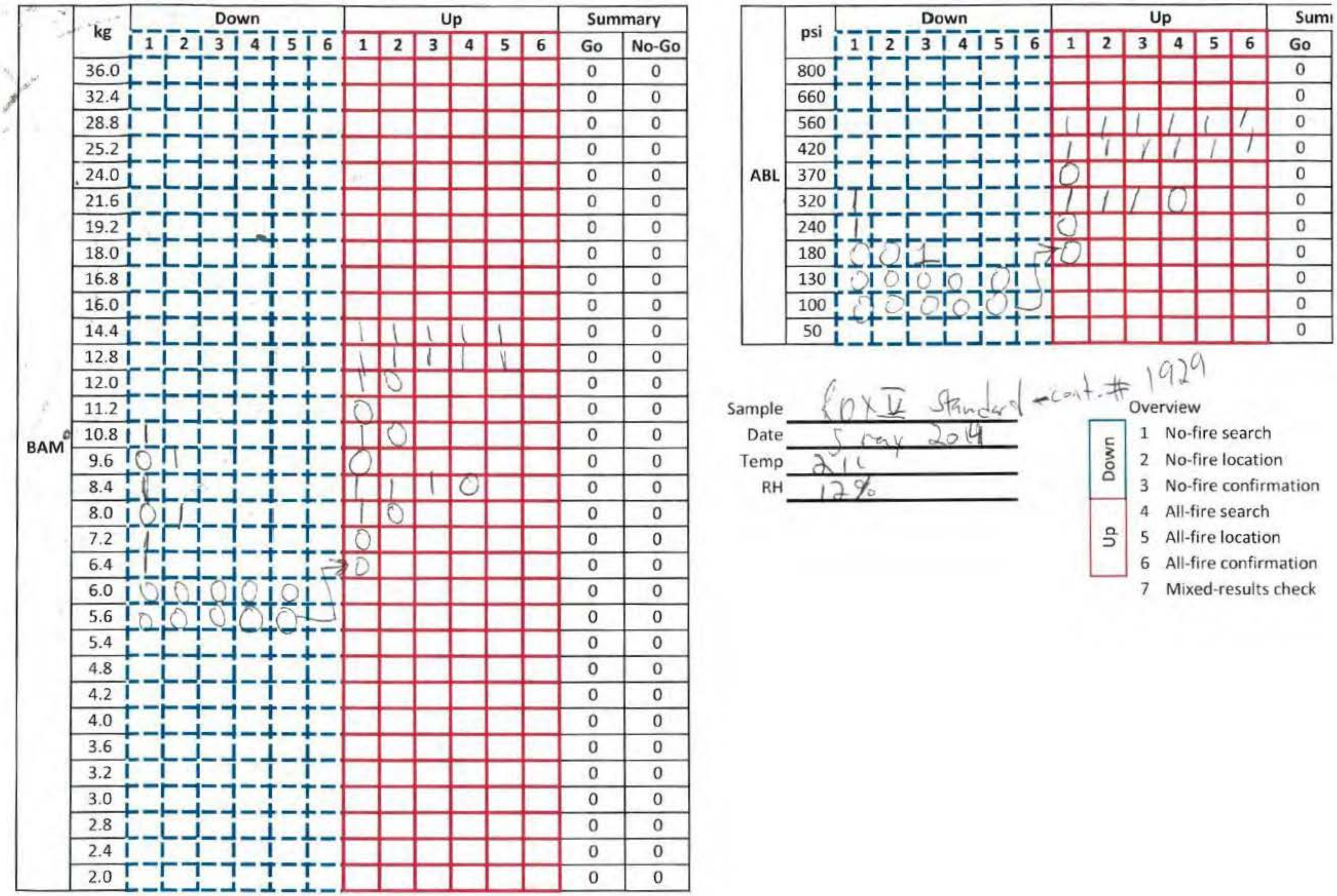


Figure A-41. Raw data sheet for RDX Class V

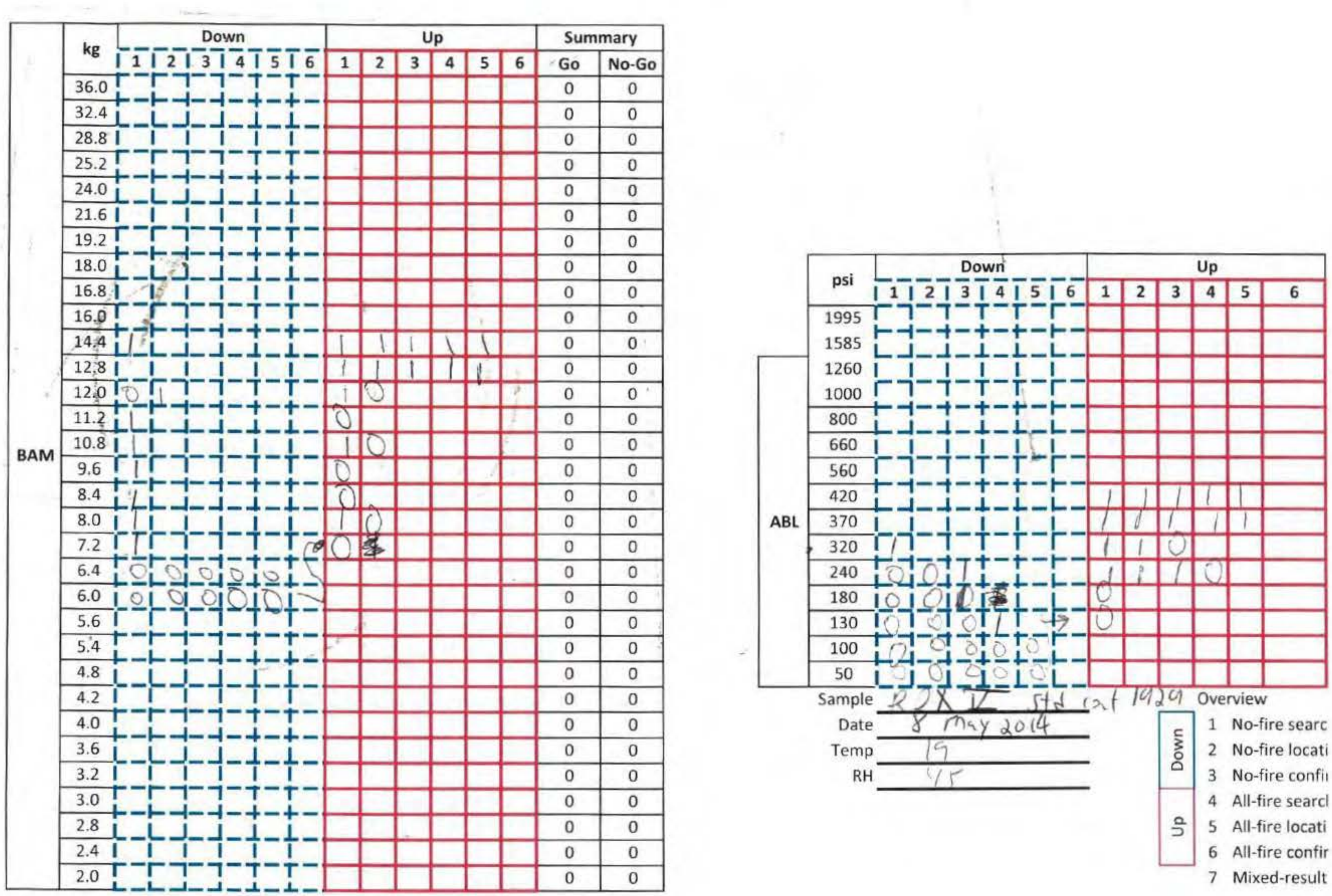


Figure A-42. Raw data sheet for RDX Class V

BAM

kg	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go	Summary No-Go
36.0													0	0
32.4													0	0
28.8													0	0
25.2													0	0
24.0													0	0
21.6													0	0
19.2													0	0
18.0													0	0
16.8													0	0
16.0	1												0	0
14.4	1												0	0
12.8	1												0	0
12.0	1												0	0
11.2	1						1	1	1	1	1		0	0
10.8	1						1	1	1	1	1		0	0
9.6	1						1	0					0	0
8.4	0	0	1				0						0	0
8.0	1						0						0	0
7.2	1						1	0					0	0
6.4	0	0	0	0	0		1	0					0	0
6.0	0	0	0	1			0						0	0
5.6	0	0	0	0	0								0	0
5.4	~~0~~	~~0~~	~~0~~	~~0~~	~~0~~								0	0
4.8													0	0
4.2													0	0
4.0													0	0
3.6													0	0
3.2													0	0
3.0													0	0
2.8													0	0
2.4													0	0
2.0													0	0

[illegible] test form [illegible]

No fill - Just [illegible]

Last level where we didn't get 5 tests

ABL

psi	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go
800													0
660	1												0
560	1						1	1	1	1	1	1	0
420	1						1	1	1	1	1	1	0
370	1						1	0					0
320	1						0						0
240	0	1					0						0
180	0	0	0	0	0								0
130	0	0	0	0	0								0
100													0
50													0

Sample: [illegible]-V

Date: 6 Feb 2014

Temp: 19.4C 22% RH

RH: 22%

Overview

- Down
  1. No-fire search
  2. No-fire location
  3. No-fire confirmation
- Up
  4. All-fire search
  5. All-fire location
  6. All-fire confirmation
  7. Mixed-results check

Figure A-43. Raw data sheet for RDX Class V

BAM	kg	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go	Summary No-Go
	36.0													0	0
	32.4													0	0
	28.8													0	0
	25.2													0	0
	24.0													0	0
	21.6													0	0
	19.2													0	0
	18.0													0	0
	16.8													0	0
	16.0													0	0
	14.4													0	0
	12.8													0	0
	12.0													0	0
	11.2													0	0
	10.8													0	0
	9.6													0	0
	8.4	|						|	|	|	|	|		0	0
	8.0	|						|	|	|	|	|		0	0
	7.2	|						|	|	O				0	0
	6.4	O	|					O						0	0
	6.0	O	|					|	O					0	0
	5.6	|						O						0	0
	5.4	|						O						0	0
	4.8	O	O					O						0	0
	4.2	O	O	O	O	O								0	0
	4.0	O	O	O	O	O								0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

ABL	psi	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Sum Go
	800													0
	660													0
	560													0
	420													0
	370													0
	320							|	|	|	|	|		0
	240	|						|			|	|		0
	180	O	|					O						0
	130	O	|					O						0
	100	|						O						0
	50	|												0

25 0 0 0 0 0
17

Sample HMX V Cont 1673
Date 8 May 2014
Temp 19
RH 17

42 2e;oJ

Overview

Down
1 No-fire search
2 No-fire location
3 No-fire confirmation

Up
4 All-fire search
5 All-fire location
6 All-fire confirmation
7 Mixed-results check

Figure A-44. Raw data sheet for HMX Class V

BAM	kg	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go	Summary No-Go
	36.0													0	0
	32.4													0	0
	28.8													0	0
	25.2													0	0
	24.0													0	0
	21.6													0	0
	19.2													0	0
	18.0													0	0
	16.8													0	0
	16.0	/												0	0
	14.4													0	0
	12.8													0	0
	12.0													0	0
	11.2													0	0
	10.8	/						/	/	/	/	/		0	0
	9.6	O	O	O	/									0	0
	8.4	/						/	/	/	/	/		0	0
	8.0	/						/	/	/	/	/		0	0
	7.2	O	O	/				O						0	0
	6.4	/						O						0	0
	6.0	/						O						0	0
	5.6	O	O	O	O	O								0	0
	5.4	/												0	0
	4.8	O	O	O	O	O								0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

ABL	psi	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Sum Go
	800	/												0
	660	/												0
	560	/												0
	420	/												0
	370	/												0
	320	/						/	/	/	/	/		0
	240	/						/	O					0
	180	O	/					/	/	/	/	/		0
	130	O	/					/	/	O				0
	100	/						/	/	O				0
	50	O	O	O	O	O								0
	25	O	O	O	O	O								

Sample HMX-5 BAE (FINE PARTICLE SIZE)

Date 11 FEB 14

Temp 17 °C

RH 60 %

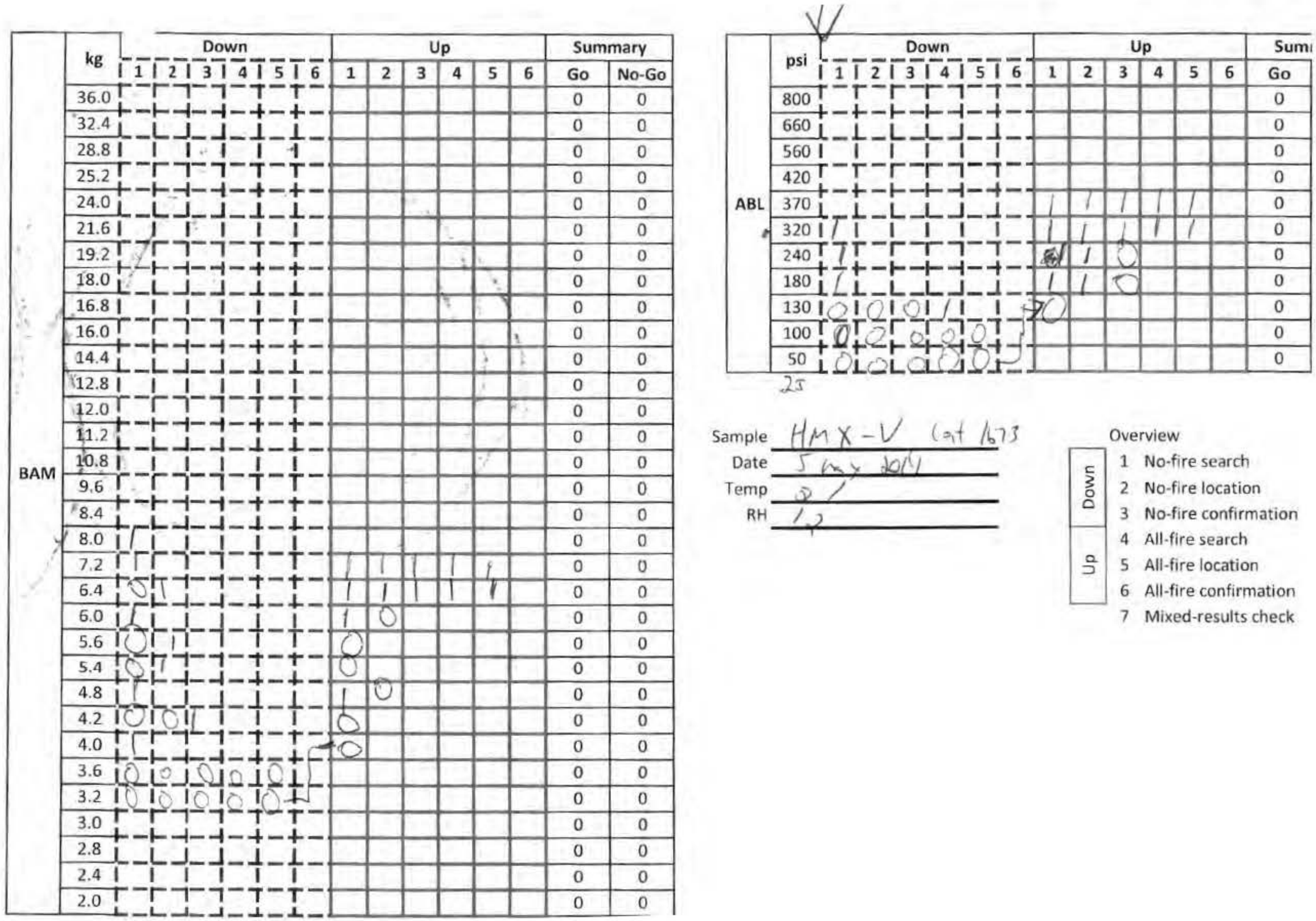
Overview

Down
1 No-fire search
2 No-fire location
3 No-fire confirmation

Up
4 All-fire search
5 All-fire location
6 All-fire confirmation

7 Mixed-results check

Figure A-45. Raw data sheet for HMX Class V



BAM kg	Down 1	2	3	4	5	6	Up 1	2	3	4	5	6	Summary Go	No-Go
36.0													0	0
32.4													0	0
28.8													0	0
25.2													0	0
24.0													0	0
21.6													0	0
19.2													0	0
18.0													0	0
16.8													0	0
16.0													0	0
14.4													0	0
12.8													0	0
12.0													0	0
11.2													0	0
10.8													0	0
9.6													0	0
8.4													0	0
8.0	/												0	0
7.2	/						/	/	/	/	/		0	0
6.4	0	/					/	/	/	/	/		0	0
6.0	/						/	0					0	0
5.6	0	/					0						0	0
5.4	0	/					0						0	0
4.8	/						/	0					0	0
4.2	0	0	/				0						0	0
4.0	/						0						0	0
3.6	0	0	0	0	0								0	0
3.2	0	0	0	0	0								0	0
3.0													0	0
2.8													0	0
2.4													0	0
2.0													0	0

ABL psi	Down 1	2	3	4	5	6	Up 1	2	3	4	5	6	Sum Go
800													0
660													0
560													0
420													0
370							/	/	/	/	/		0
320	/						/	/	/	/	/		0
240	/							/	0				0
180	/						/	/	0				0
130	0	0	0	/	/		0						0
100	0	0	0	0	0								0
50	0	0	0	0	0								0

25

Sample HMX-V Lot 1673

Date 5 May 2014

Temp

RH

Overview

Down
1 No-fire search
2 No-fire location
3 No-fire confirmation

Up
4 All-fire search
5 All-fire location
6 All-fire confirmation
7 Mixed-results check

Figure A-46. Raw data sheet for HMX Class V

	kg	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go	Summary No-Go
BAM	36.0							|	|	|	|	|	|	0	0
	32.4							|	|	O		|		0	0
	28.8							O						0	0
	25.2							|	|	O				0	0
	24.0	|						[illegible]	|	O				0	0
	21.6	|						O						0	0
	19.2	|						O						0	0
	18.0	|						O						0	0
	16.8	|						O	[illegible]					0	0
	16.0	|						O						0	0
	14.4	O	O	O	O	O								0	0
	12.8	O	O	O	O	O								0	0
	12.0													0	0
	11.2													0	0
	10.8													0	0
	9.6													0	0
	8.4													0	0
	8.0													0	0
	7.2													0	0
	6.4													0	0
	6.0													0	0
	5.6													0	0
	5.4													0	0
	4.8													0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

	psi	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6
	1995												
	1585												
ABL	1260							|	|	|	|	|	
	1000	|						|	|	|	|	|	
	800	|						|	O				
	660	|					[illegible]	O	[illegible]				
	560	|					[illegible]	|	O				
	420	|						O					
	370	O	O	O	O	[illegible]							
	320	O	O	O	O								
	240												
	180												
	130												
	100												
	50												

Sample MNX 808
Date 12 MAY 14
Temp 18.8
RH 16

Overview
Down
1 No-fire searc
2 No-fire locati
3 No-fire confi
Up
4 All-fire searcl
5 All-fire locati
6 All-fire confir
7 Mixed-result

Cut from Puck
#PBX110 was
cut strips!

Figure A-47. Raw data sheet for MNX-808

	kg	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go	Summary No-Go
BAM	36.0							I	I	I	I	I	I	0	0
	32.4							I	O					0	0
	28.8							I	O					0	0
	25.2	I						O						0	0
	24.0	I						I	O					0	0
	21.6	I						O						0	0
	19.2	O	O	I				O						0	0
	18.0	O	I					O						0	0
	16.8	I						O						0	0
	16.0	O	O	O	O	I		O						0	0
	14.4	O	O	O	O	O								0	0
	12.8	O	O	O	O	O								0	0
	12.0													0	0
	11.2													0	0
	10.8													0	0
	9.6													0	0
	8.4													0	0
	8.0													0	0
	7.2													0	0
	6.4													0	0
	6.0													0	0
	5.6													0	0
	5.4													0	0
	4.8													0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

	psi	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6
	1995												
	1585							I	I	I	I	I	
ABL	1260							I	I	I	I	I	
	1000	I						O					
	800	O	O	O	O	O							
	660	O	O	O	O	O							
	560												
	420												
	370												
	320												
	240												
	180												
	130												
	100												
	50												

Sample: MNX 808
Date: 7 May 2011
Temp: 19C
RH: 13%

Cut from Puck

Overview

Down
1 No-fire searc
2 No-fire locati
3 No-fire confi

Up
4 All-fire searcl
5 All-fire locati
6 All-fire confir
7 Mixed-result

Figure A-48. Raw data sheet for MNX-808

	kg	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go	Summary No-Go
	36.0													0	0
	32.4							1	1	1	1	1		0	0
	28.8							1	1	1	1	1		0	0
	25.2	1						1	1	1	0			0	0
	24.0	0	0	0	0	0								0	0
	21.6	1	1	0										0	0
	19.2	0	0	0	0	0								0	0
	18.0	0	0	1										0	0
	16.8	0	0	0	0	0								0	0
	16.0													0	0
	14.4													0	0
	12.8													0	0
	12.0													0	0
	11.2													0	0
BAM	10.8													0	0
	9.6													0	0
	8.4													0	0
	8.0													0	0
	7.2													0	0
	6.4													0	0
	6.0													0	0
	5.6													0	0
	5.4													0	0
	4.8													0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

	psi	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Sum Go
	800	0	0	0	0	0								0
	660	0	0	1										0
	560	0	0	0	0	0								0
	420													0
ABL	370													0
	320													0
	240													0
	180													0
	130													0
	100													0
	50													0

Sample MNX 808
Date 13 FEB 14
Temp 16.4 C
RH 31%

	DOWN	UP
1000	01	
1260	1	110
1585		110
1995		11111.

Overview

Down
1 No-fire search
2 No-fire location
3 No-fire confirmation

Up
4 All-fire search
5 All-fire location
6 All-fire confirmation

7 Mixed-results check

* - ON SOME OF THE MIXES, IT'S POSSIBLE THAT THE FRICTION TEST IS NOT GETTING THE EXPLOSIVE, ONLY THE BINDING AGENT

Figure A-49. Raw data sheet for MNX-808

BAM														
kg	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go	Summary No-Go
36.0													0	0
32.4													0	0
28.8													0	0
25.2							/	/	/	/	/		0	0
24.0	/						/	/	/	/	/		0	0
21.6	O	O	O	/									0	0
19.2	O	O	/										0	0
18.0	O	/											0	0
16.8	/												0	0
16.0	O	O	O	/									0	0
14.4	O	O	O	O	/								0	0
12.8	O	O	O	O	O	O							0	0
12.0	O	O	O	O	O								0	0
11.2													0	0
10.8													0	0
9.6													0	0
8.4													0	0
8.0													0	0
7.2													0	0
6.4													0	0
6.0													0	0
5.6													0	0
5.4													0	0
4.8													0	0
4.2													0	0
4.0													0	0
3.6													0	0
3.2													0	0
3.0													0	0
2.8													0	0
2.4													0	0
2.0													0	0

ABL													
psi	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Sum Go
800	O	O	/										0
660	/												0
560	O	O	O	O	O								0
420	O	O	O	O	O								0
370													0
320													0
240													0
180													0
130													0
100													0
50													0

Sample PBXN 5 109
Date 13 Feb 14
Temp 16.4C
RH 31%

	Down	UP
1000	/	/O
1260	/	/////
1585	/	/////
1995	/	

Overview

Down
1 No-fire search
2 No-fire location
3 No-fire confirmation

Up
4 All-fire search
5 All-fire location
6 All-fire confirmation
7 Mixed-results check

Figure A-50. Raw data sheet for PBXN-109

	kg	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go	Summary No-Go
BAM	36.0							1	1	0	0	1	1	0	0
	32.4							1	1	1	1	1		0	0
	28.8							0						0	0
	25.2							0						0	0
	24.0	1					[illegible]	1	0	~~[illegible]~~				0	0
	21.6	0	0	0	0	0								0	0
	19.2	0	0	0	0	0								0	0
	18.0													0	0
	16.8													0	0
	16.0													0	0
	14.4													0	0
	12.8													0	0
	12.0													0	0
	11.2													0	0
	10.8													0	0
	9.6													0	0
	8.4													0	0
	8.0													0	0
	7.2													0	0
	6.4													0	0
	6.0													0	0
	5.6													0	0
	5.4													0	0
	4.8													0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

	psi	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6
	1995												
	1585							1	1	1	1	1	
ABL	1260	1						1	1	1	1	1	
	1000	1						0					
	800	1						1	0				
	660	0	1					0					
	560	0	0	0	0	0		0					
	420	0	0	0	1			0					
	370	0	0	0	0	0							
	320	0	0	0	0	0							
	240												
	180												
	130												
	100												
	50												

Sample PBX 110
Date 12 May 14
Temp 18.8
RH 463

Overview

Down	1	No-fire searc
	2	No-fire locati
	3	No-fire confi
Up	4	All-fire searcl
	5	All-fire locati
	6	All-fire confir
	7	Mixed-result

Figure A-51. Raw Data sheet for PBXN-110

BAM	kg	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go	Summary No-Go
	36.0							1	1	1	1	1	1	0	0
	32.4							0						0	0
	28.8	1						0						0	0
	25.2	1						0						0	0
	24.0	0	0	1				1	0					0	0
	21.6	0	0	0	0	0								0	0
	19.2	0	0	0	0	0								0	0
	18.0													0	0
	16.8													0	0
	16.0													0	0
	14.4													0	0
	12.8													0	0
	12.0													0	0
	11.2													0	0
	10.8													0	0
	9.6													0	0
	8.4													0	0
	8.0													0	0
	7.2													0	0
	6.4													0	0
	6.0													0	0
	5.6													0	0
	5.4													0	0
	4.8													0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

ABL	psi	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6
	1995	1						1	1	1	1	1	
	1585	1						1	1	1	1	1	
	1260	1						1	0				
	1000	1						0					
	800	0	0	0	1			0					
	660	0	1					0					
	560	0	0	1				1	0				
	420	0	0	0	0	0							
	370	0	0	0	0	0							
	320												
	240												
	180												
	130												
	100												
	50												

Sample PBX-110
Date 7 May 2014
Temp 19.0
RH 48 %

Overview

Down	1	No-fire searc
	2	No-fire locati
	3	No-fire confi
Up	4	All-fire searcl
	5	All-fire locati
	6	All-fire confir
	7	Mixed-result

Figure A-52. Raw data sheet for PBXN-110

BAM	kg	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Summary Go	Summary No-Go
	36.0							/	/	/	/	/		0	0
	32.4							/	/	/	/	/		0	0
	28.8							/	/	/	O			0	0
	25.2							O						0	0
	24.0	O	/					/	/	O				0	0
	21.6	O	O	O	/			O						0	0
	19.2	O	/					/	O					0	0
	18.0	O	O	O	/									0	0
	16.8	O	O	O	O	O	O							0	0
	16.0	O	O	O	O	O								0	0
	14.4													0	0
	12.8													0	0
	12.0													0	0
	11.2													0	0
	10.8													0	0
	9.6													0	0
	8.4													0	0
	8.0													0	0
	7.2													0	0
	6.4													0	0
	6.0													0	0
	5.6													0	0
	5.4													0	0
	4.8													0	0
	4.2													0	0
	4.0													0	0
	3.6													0	0
	3.2													0	0
	3.0													0	0
	2.8													0	0
	2.4													0	0
	2.0													0	0

Thickess X .5" Long X .5 long

.030 - .040 Sample All PBX's B far.

ABL	psi	Down 1	Down 2	Down 3	Down 4	Down 5	Down 6	Up 1	Up 2	Up 3	Up 4	Up 5	Up 6	Sum Go
	800	O	O	/										0
	660	O	/											0
	560	/												0
	420	O	O	O	O	O								0
	370	O	O	O	O	O								0
	320													0
	240													0
	180													0
	130													0
	100													0
	50													0

Sample PBXN 5 110
Date 12 FEB
Temp 17
RH 46

Overview
Down
1 No-fire search
2 No-fire location
3 No-fire confirmation
Up
4 All-fire search
5 All-fire location
6 All-fire confirmation
7 Mixed-results check

	Run	UP
1000	/	
1260	/	/////
1585	* O /	/////
1915		/////

* - WE WERE GETTING NO-GO UNTIL CRAIG SLICED SAMPLES TO REDUCE THICKNESS IT IS POSSIBLE THE 1585 WAS AN UNCUT SAMPLE.

Figure A-53. Raw data sheet for PBXN-110

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